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## MANUFACTURING TECHNOLOGY RESEARCH NEEDS OF THE GEAR INDUSTRY

December 1987

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**MANUFACTURING TECHNOLOGY RESEARCH NEEDS  
OF THE GEAR INDUSTRY**

**Defense Logistics Agency  
Cameron Station  
Alexandria, Virginia 22304-6100**

**Attention: Dan Gearing**

**Contract DLA900-84-C-1508**

**IITRI Project P06066**

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Chicago, Illinois 60616-3799**

**31 December 1987**

## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Unclassified Distribution Unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) IITRI-P06066-1			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Cresap, McCormick and Paget Division of TPF&C Inc.		6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION Dr. Lloyd Lehn, Asst. for Manufacturing Technology		
6c. ADDRESS (City, State, and ZIP Code) 10 West 35 Street, Chicago, IL 60616-3799			7b. ADDRESS (City, State, and ZIP Code) Office of the Asst. Secretary of Defense Pentagon, Room 3C 257 Washington, DC 20302-8000		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Defense Logistics Agency		8b. OFFICE SYMBOL (if applicable) DLA-PR	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DLA-900-84-C-1508		
8c. ADDRESS (City, State, and ZIP Code) Cameron Station Alexandria, VA 22304-6100			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO. 780015	PROJECT NO.	TASK NO.
					WORK UNIT ACCESSION NO. DS000103
11. TITLE (Include Security Classification) MANUFACTURING TECHNOLOGY RESEARCH NEEDS OF THE GEAR INDUSTRY					
12. PERSONAL AUTHOR(S) Maurice A. H. Howes					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 87-1-29 TO 87-12-28		14. DATE OF REPORT (Year, Month, Day) 1987-12-31	
15. PAGE COUNT 102					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
13	08		Aircraft gears, industries, manufacturing		
01	03				
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Gears are fundamental and essential components of most defense as well as civilian machinery and equipment: Because of their widespread usage and critical applications, they are essential to industrial mobilization. The U.S. retention of adequate capability to satisfy the demand for these products during any emergency is vital to a strong defense posture. The U.S. capacity to produce gears is dwindling as imported products continue to displace U.S. gears at home and abroad.</p> <p>This study was undertaken to identify the current state of the U.S. gear industry and help define a course of action that might be taken to improve U.S. manufacturing of gears. The specific tasks were:</p> <ol style="list-style-type: none"> <li>1. Assess current manufacturing processes and review ongoing manufacturing technology research programs for gears.</li> </ol>					
(Continued)					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Robert A. Walk			22b. TELEPHONE (Include Area Code) 312/567-7730		22c. OFFICE SYMBOL

## 19. ABSTRACT (continued)

2. Identify manufacturing technology research needs and opportunities that will make the greatest long-range impact on the health and international competitiveness of the U.S. gear industry.
3. Identify technology which is commercially available today that would assist the gear industry to become internationally competitive but which is not being used, and which might be the subject of an industrial modernization incentive program.

## ABSTRACT

Gears are fundamental and essential components of most defense as well as civilian machinery and equipment. Because of their widespread usage and critical applications, they are essential to industrial mobilization. The U.S. retention of adequate capability to satisfy the demand for these products during any emergency is vital to a strong defense posture. The U.S. capacity to produce gears is dwindling as imported products continue to displace U.S. gears at home and abroad.

This study was undertaken to identify the current state of the U.S. gear industry and help define a course of action that might be taken to improve U.S. manufacturing of gears. The specific tasks were:

- 1) Assess current manufacturing processes and review ongoing manufacturing technology research programs for gears.
- 2) Identify manufacturing technology research needs and opportunities that will make the greatest long-range impact on the health and international competitiveness of the U.S. gear industry. *and*
- 3) Identify technology which is commercially available today that would assist the gear industry to become internationally competitive but which is not being used, and which might be the subject of an industrial modernization incentive program. *aircraft gears*



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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

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## GLOSSARY OF TERMS

ADI	Austempered Ductile Iron
AGMA	American Gear Manufacturers Association
AGV	Automatic Guided Vehicle
AI	Artificial Intelligence
ASME	American Society of Mechanical Engineers
AWACS	Airborne Warning and Control System
BGA	British Gear Association
BGMA	British Gear Manufacturers Association
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CBN	Cubic Boron Nitride
CETIM	Centre d'Etudes Techniques des Industries Mecaniques
CIM	Computer-Integrated Manufacturing
CIRP	College International pour l'Etude Scientifiques des Techniques de Production Mecanique
CNC	Computer Numerical Control
CPU	Central Processing Unit
DCSC	Defense Construction Supply Center
DLA	Defense Logistics Agency
EPA	Environmental Protection Agency
ESPRIT	European Strategic Program for Research into Information Technology
FMS	Flexible Manufacturing Systems or Flexible Machining Systems
FVA	Forschungsvereinigung Antriebstechnik
GRI	Gear Research Institute
HIP	Hot Isostatic Pressing
IMechE	Institute of Mechanical Engineers
IMIP	Industrial Modernization Incentive Program
INFAC	Instrumented Factory
IITRI	IIT Research Institute
JIT	Just in Time
MMC	Metal Matrix Composites
MRP	Manufacturing Resource Planning

NC	Numerical Control
NNS	Near Net Shape
NSF-ERC	National Science Foundation-Engineering Research Center
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
OSU	Ohio State University
SB	Spiral Bevel
SIC	Standard Industrial Classification
SOP	Standard Operating Procedure
TiN	Titanium Nitride
WIP	Work in Progress

## 1. INTRODUCTION

A previous Defense Logistics Agency (DLA) study by the Defense Construction Supply Center (DCSC), Columbus, Ohio, reviewed U.S. Department of Commerce reports on annual shipment value levels of gears and concluded that foreign inroads began in the domestic gear market in 1979 and continued through 1983. Although the value of shipments stabilized in 1984, this has not provided much consolation to U.S. gear manufacturers. Recent conversations with prime helicopter makers has indicated that many aircraft quality gears are being made overseas, particularly in Italy and England, and incorporated in gear base assemblies. The identity of the gear manufacturer may not be known to the ultimate user who often believes that his helicopter is totally U.S. made.

The dangers of this practice to our defense posture are obvious. First, it is not immediately ascertainable if gears would be available for new craft and as spare parts in an emergency situation such as the country of gear origin being invaded by a potential enemy. Secondly, since less gears are ordered in the United States, the industry shrinks, profits dwindle, and less money is available for investment in modernization of plants. It is not likely that a shrinking industry would be modernized under normal business conditions. Lastly, if there is a sudden additional demand for gears, it becomes less likely that the equipment and skilled personnel would be available.

This condition reflects back to the machine tool industry. In the tooth generating machine area (i.e., shaping, hobbing, grinding), the United States is only one deep in machine tool makers. Lack of business has forced the closure of many companies and those still in existence are not healthy companies. They are in a desperate fight for survival. Although they realize that more advanced machines are needed to compete with or leapfrog foreign competition, they have only limited funds to advance new developments. In general, their customers are the U.S. auto or allied industries and overseas companies and only to a limited degree the U.S. aerospace gear industry. As a result, manufacturing technology for aerospace gears is stagnant.

While the aerospace gear industry has significant competition from overseas, the high volume commercial gear market has lost even more business to overseas producers. However, automotive gear suppliers are realizing this and there are now examples of high production computer-integrated manufacturing (CIM) coming on line. This is not the case in the precision gear market where it might be supposed that a flexible manufacturing system (FMS) would be ideal for the small quantities involved and it is believed that only one company is contemplating a state of the art gear factory.

These introductory remarks paint a grim picture and that is an accurate assessment of the state of the precision gear industry. A mechanism is needed for the U.S. precision gear industry to be assured of a stable market with some of the purchasing practices modified and for the plants to be modernized so that high quality gears can be produced effectively and competitively.

## 2. CURRENT MANUFACTURING PROCESSES

### 2.1 METHODOLOGY OF STUDY

For this study a variety of gear makers and companies associated with gear making were visited. The prime companies of interest were U.S. makers of aerospace-quality gears, but for comparison purposes, nonaerospace and foreign gear makers and builders of machine tools were also visited. The following companies were visited:

#### (a) U.S. Aerospace Gear Makers

ACR	Roseville, MI
Aircraft Gear	Bedford Park, IL
Allison	Indianapolis, IN
Arrow Gear	Downers Grove, IL
Bell	Fort Worth, TX
Candale Precision	Roseville, MI
Indiana Gear	Indianapolis, IN
Litton	Chicago, IL
Sikorsky	Stratford, CT
Speco	Springfield, OH
Summit Gear	Minneapolis, MN
Supreme Gear	Roseville, MI
Western Gear	City of Industry, CA

#### (b) Nonaerospace Gear Makers

Borg-Warner	Muncie, IN
ITW Woodworth	Ferndale, MI



- (c) Foreign Gear Makers
- |                      |                         |
|----------------------|-------------------------|
| Hansen Transmissions | Edegem, Belgium         |
| Verzahntechnik       | Ettlingen, West Germany |
| Voith Transmissions  | Ulm, West Germany       |
| Watteum*             | Ghent, Belgium          |
| Westland             | Yoevil, England         |
- (d) Machine Tool Makers
- |                        |                            |
|------------------------|----------------------------|
| Fellows                | Springfield, VT            |
| Gleason Works          | Baudour, Belgium           |
| Gleason Works          | Rochester, NY              |
| Guhring Automation     | Frohnstetten, West Germany |
| Lorenz                 | Ettlingen, West Germany    |
| Maag                   | Zurich, Switzerland        |
| National Broach        | Mt. Clemens, MI            |
| Pfauter                | Ludwigsburg, West Germany  |
| Reishaur               | Zurich, Switzerland        |
| Weiner Gear Technology | Ettlingen, West Germany    |
- (e) Prime Aerospace Companies
- |                 |                 |
|-----------------|-----------------|
| Bell**          | Fort Worth, TX  |
| Kaman Aerospace | Bloomfield, CT  |
| Sikorsky**      | Stratford, CT   |
| Westland**      | Yoevil, England |
- (f) Universities
- |   |                      |
|---|----------------------|
| Technical University<br>of Aachen                           | Aachen, West Germany |
| Technical University<br>of Munich<br>(Gear Research Center) | Munich, West Germany |
| Ohio State University                                       | Columbus, OH         |
- (g) AGMA Gear Expo and 1987 Fall Technical Meeting
- (h) ASME Gear Research Institute      Naperville, IL

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\*Believed to make gears for Airbus.

\*\*Also aerospace gear makers.

## 2.2 GEAR MANUFACTURERS

### 2.2.1 Introduction

Companies rarely manufacture both commercial gears and precision gears. Precision gears are usually considered to be gears manufactured to the American Gear Manufacturers Association (AGMA) levels 11 through 15. For aerospace use, the majority (90%) of gears are used in helicopters as main drive and ancillary gears. For nonhelicopter use, i.e., fixed wing aircraft, precision gears are found principally in ancillary power take-offs, flap actuators, and undercarriage mechanisms. The helicopter models being produced or considered for production are listed in Table 1.

### 2.2.2 Precision Gear Makers

A study of AGMA consumption statistics reveals that eight companies provide 80 to 90 percent of the aerospace gears made in North America. These companies are:

Aircraft Gear	Sikorsky
Bell	Spar
Indiana Gear	Speco
Litton	Western

Spar is a Canadian company and is the only plant not visited during this study. An additional five companies were visited which contribute to the 10 to 20 percent remaining gears. It is difficult to estimate the number of non-U.S.-made precision gears being used in the building of new or reconditioned helicopters and as spare parts in complete gear boxes but it probably represents 20 to 30 percent of the gears used. Companies do not go out of their way to advertise the use of non-U.S.-made gears and often are forced to buy them through memoranda of understanding or reciprocal agreements to buy components when an overseas government buys complete helicopters. However, it is certain that gears bought overseas do not just go into craft shipped overseas, but also into the product sold in the United States. This is because component quantities are relatively small and it often increases costs to split gear orders and have two lots of data packages, tooling and master gears.

**TABLE 1. HELICOPTER MODELS PRODUCED  
OR CONSIDERED FOR PRODUCTION**

---

Bell 205/UH-1  
Bell 206/TH-57  
Bell 209/AH-1  
Bell 212  
Bell 214  
Bell 222  
Bell 406/OH-58D  
412  
Bell-Boeing V-22  
Boeing-Vertol CH47/414/100  
Evistrom F28  
Evistrom 280  
Hiller 12E/12ET  
Hiller FH1100  
Hughes 300  
Hughes 500/530  
Hughes AH-64  
Kaman SH-2F  
LHX  
Robinson R22  
Sikorsky S-61  
Sikorsky S-65/CH-53E  
Sikorsky S-70/UH-60A/HH-60  
Sikorsky S70B/SH-60B  
Sikorsky S-76/H-76

---

### **2.2.3 Aerospace Gears**

The products described as aerospace gears are very often a compromise between what the designer would like and what it is possible to manufacture. Gears must transmit high power levels at the lowest possible weight. This requires thin sections with all possible excess metal removed which causes difficulties in machining, grinding, and controlling distortion during heat treatment. To save weight, many gears are much more complex than those shown in Figures 1 to 19. They often consist of several gears in the same assembly together with splines, threads, keyways and oil holes, all machined to very high standards of accuracy.

### **2.2.4 Types and Classification of Gears**

There are many types of gears in existence, each serving a range of functions. In order to understand gearing, it is desirable to classify the more important types in some way. One convenient approach is by the relationship of the shaft axes on which the gears are mounted. Shafts may be parallel or nonparallel. If nonparallel, they may be intersecting or nonintersecting.

#### **2.2.4.1 Types of Gears That Operate on Parallel Shafts**

Spur Gears. Cylindrical in form and have teeth which are of involute form in most cases. The tooth surface elements are all parallel to the gear axis (see Figure 1).

Helical Gears. Cylindrical in form. The teeth are generally involute form. The teeth may lie in one or two bands around the gear (see Figure 2). The teeth in pinion and gear or helical gears must be of opposite hand. The tooth elements are helices about the axis of the gear.

Single Helical Gears. If the teeth lie in a single band, the gear is called single helical (see Figure 3).

Double Helical Gears. If the teeth lie in two bands with a narrow non-toothed zone between, the gears are called double helical. The helices are of opposite hands (see Figure 4).

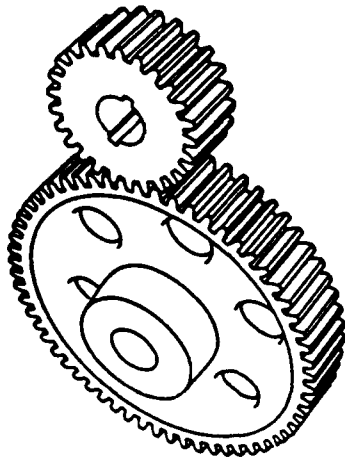


Figure 1. Spur gears.

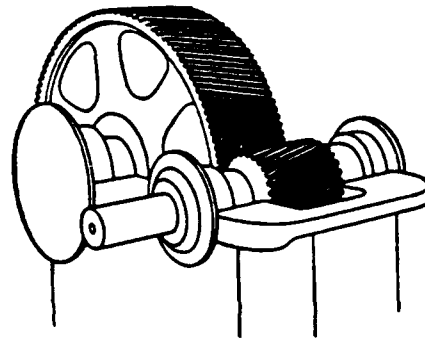


Figure 2. Helical gears.

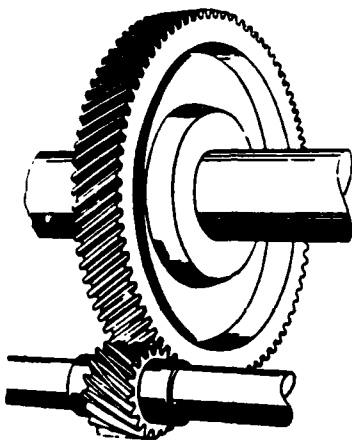


Figure 3. Single helical gears.

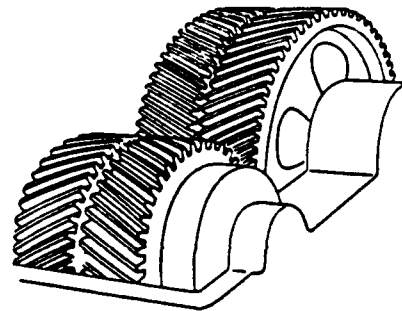


Figure 4. Double helical gears.

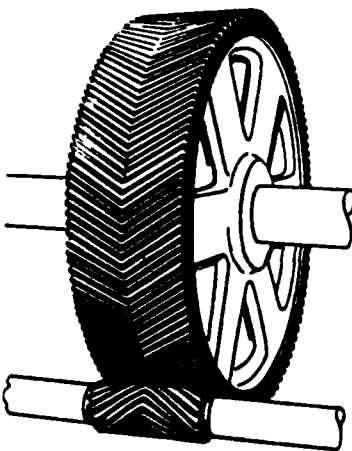


Figure 5. Herringbone gears.

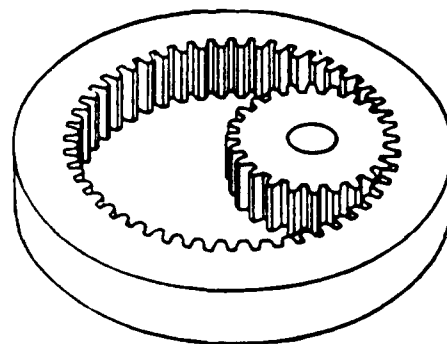


Figure 6. Internal gears.

Source: Gear Manufacture and Performance, ASM, 1974.

Herringbone Gears. If the teeth lie in two bands which join, the gears have a herringbone appearance and are so called (see Figure 5).

Internal Gears. Cylindrical in form and have either spur or helical teeth (see Figures 6). By definition, a left-handed internal helical gear is one which meshes with a left hand mating pinion.

#### **2.2.4.2 Types of Gears That Operate on Nonparallel, Intersecting Shafts**

Bevel Gears. Conical in form. The profiles of the teeth are of special generated forms depending upon the application, economics, and other factors. Various special tooth profile forms are identified as follows:

Straight Bevel Gears. Have straight tooth elements which, if extended, would pass through the point of intersection of their axes (see Figure 7).

Spiral Bevel Gears. Have teeth which are curved and oblique (see Figure 8).

Crown Gears. Have teeth which are straight or curved and which lie in a plane pitch surface.

Zerol® Bevel Gears. Have teeth which are curved but in the same general direction as straight teeth (see Figure 9).

Skew Bevel Gears. Those in which the corresponding crown gear has teeth that are straight and oblique (see Figure 10).

Miter Gears. Bevel gears having equal number of teeth and with axes at right angles.

Specialized bevel gear tooth forms are: Coniflex® which have straight teeth which are crowned; Formate® in which the gear member of the pair has nongenerated teeth, usually with straight profiles and the pinion has generated teeth that are conjugate to the gear; Revacycle® which have straight teeth generated by a special process with a special tooth form.

Face Gears. Consist of a spur or helical pinion in combination with a conjugate gear of disk form, the axes being usually at right angles, either intersecting or nonintersecting (see Figure 11).

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\*Registered in U.S. Patent Office.

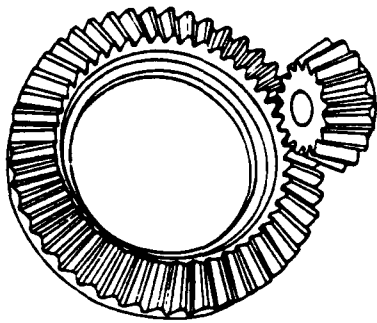


Figure 7. Straight bevel gears.

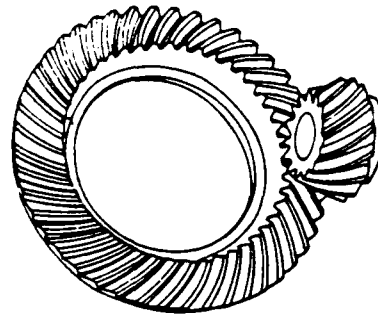


Figure 8. Spiral bevel gears.

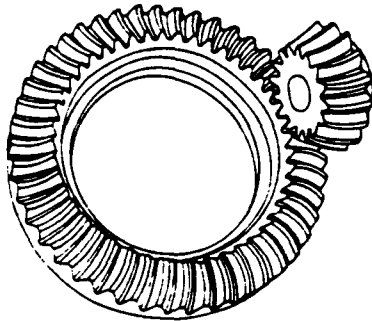


Figure 9. Zerol bevel gears.

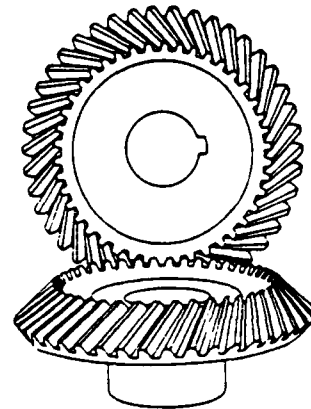


Figure 10. Skew bevel gears.

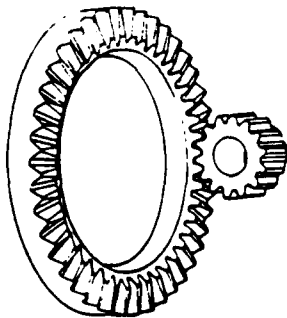


Figure 11. Face gears.

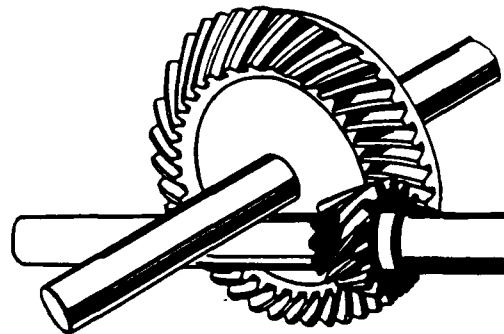


Figure 12. Hypoid gears.

Source: Gear Manufacture and Performance, ASM, 1974.

#### **2.2.4.3 Types of Gears That Operate on Nonparallel Nonintersecting Shafts**

Hypoid Gears. Similar to bevel gears, but operate on nonintersecting axes. They usually have teeth that are curved and oblique. The tooth surfaces of both gear and pinion are cut or generated by the same or similar tools (see Figure 12).

Worm Gearing. Consists of a worm and a worm gear. The axes are usually at right angles.

Worm. A gear with teeth in the form of screw threads. A frequently used tooth form is an involute helicoid.

Cylindrical worms have one or more threads in the form of screw threads on a cylinder (see Figure 13).

Hourglass worms have one or more threads and increase in diameter from the middle portion toward both ends conforming to the curvature of the mating gear. Such a worm is frequently termed enveloping (see Figure 14).

Worm Gear. A worm gear is a mate to a worm. A worm gear that is completely conjugate to its worm has line contact and is said to be single enveloping (see Figure 15).

Double-Enveloping Worm Gear. A worm gear set consisting of an hourglass worm mated with a fully conjugate throated worm gear (see Figure 16).

Crossed Helical Gears. Operate on crossed axes and may have teeth of the same or opposite hand (see Figure 17).

Spiroid® Gears. Skew axis gears, usually at right angles. The pinion member is conical in shape and the mating member is a face type gear (see Figure 18).

Helicon® and Planoid® Gears. Members of the Spiroid family. A Helicon pinion is a Spiroid without a taper.

#### **2.2.4.4 Types of Gears That Operate With Straight Line Motion**

Rack. A gear with teeth spaced along a straight line.

Spur Rack. Has straight teeth that are at right angles to the direction of motion (see Figure 19).





Figure 13. Cylindrical worm.

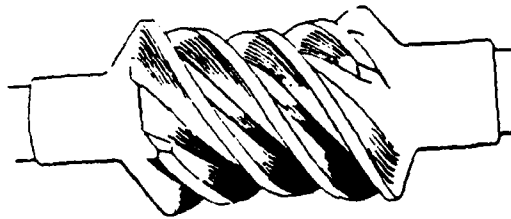


Figure 14. Hour glass worm.

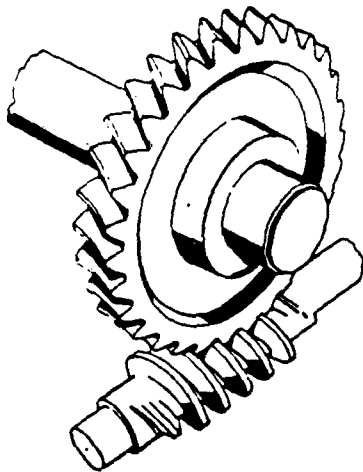


Figure 15. Single enveloping worm gears.

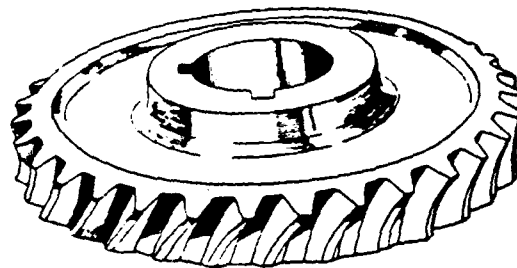


Figure 16. Double enveloping worm gear.

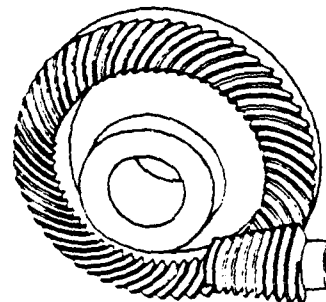


Figure 18. Spiroid gears.

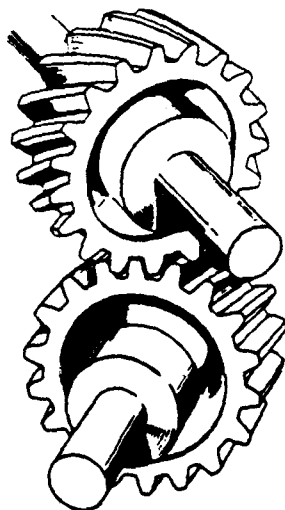


Figure 17. Crossed axis helical gears.

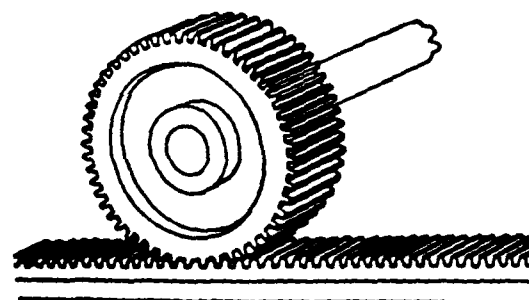


Figure 19. Spur rack and pinion.

Source: Gear Manufacture and Performance, ASM, 1974.

Helical Rack. Has straight teeth that are oblique to the direction of motion.

### **2.2.5 Terminology of Gearing**

The terminology of gearing is frequently divided into four areas. The first covers the points, lines and surfaces that describe the geometry of gears. Geometric terms are covered in detail in Section 2.2.6. The second area covers the teeth and their relationship to the gear blank. The general types of gears and their teeth were discussed in Section 2.2.4. Figure 20 shows the terminology of teeth on various types of gears. Figure 21 shows the terms used to describe spur and helical gear tooth parts. Figure 22 shows the important areas of contact and boundary zones of a gear tooth. Figure 23 shows terms covering gear blanks.

Aerospace precision gears fall into three major categories:

- o Large, heavy gears transmitting very high torque forces, such as those typically found in helicopter/tilt wing aircraft or turbo-prop engine drive-line gear boxes
- o Medium sized gears, some of which may not even rotate 360 degrees but which handle high loads. Typical uses include undercarriage retraction mechanisms, flap and control surface actuators and aircraft engine accessory driveboxes.
- o Smaller gears, say under 3 inch diameter, which may run at any speed, from very slow to very fast. These gears are used in fuel, lubrication and scavenge pumps, various types of actuators, control functions and instrumentation. In pump applications in particular, tip sealing of gear teeth to prevent or reduce leakage paths may be of great concern in the manufacturing process.

Very often gears have two or more gear forms cut into the component along with several bearing surfaces and splines. There may be deep oil holes (i.e., over 20 diameters deep), threads and retaining ring grooves. The gear may be long compared with the diameter. Each of these features need specialized and expensive equipment and tooling and complicated heat treatment processing.

### **2.2.6 Precision Gear Manufacturers**

To maintain confidentiality, gear manufacturers are not described individually. Most companies use essentially similar manufacturing steps with very little proprietary methods in use. The main variable is the equipment in

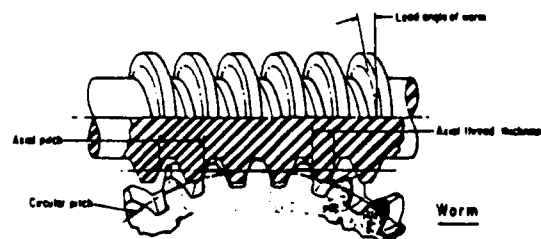
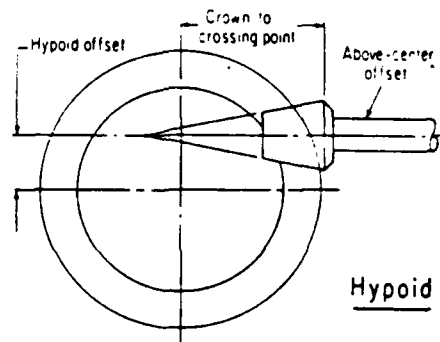
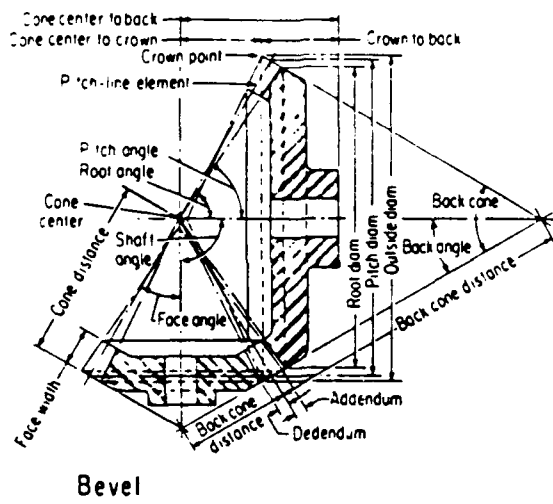
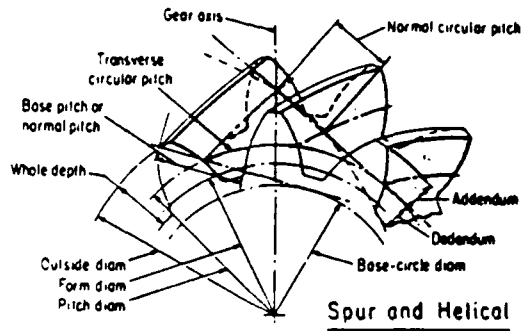
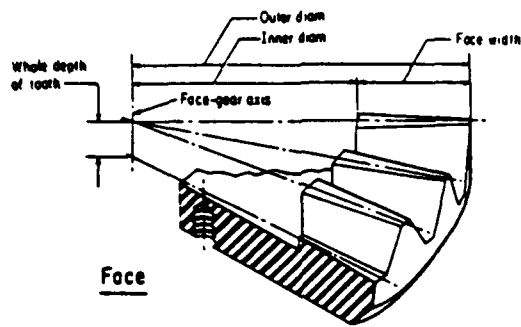


Figure 20. Nomenclature of the elements of gear geometry.

Source: Gear Manufacture and Performance, ASM, 1974.

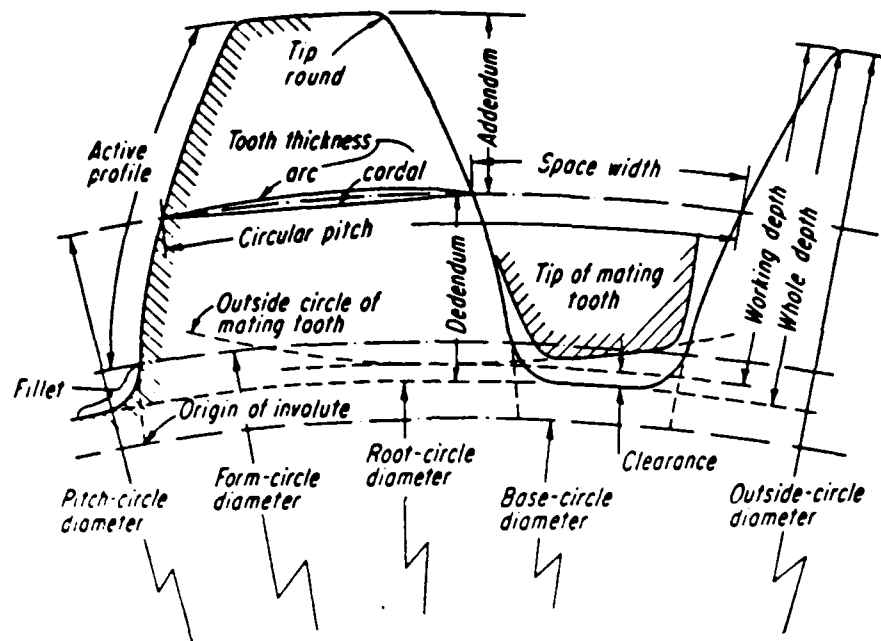


Figure 21. Nomenclature of the elements of spur and helical teeth.

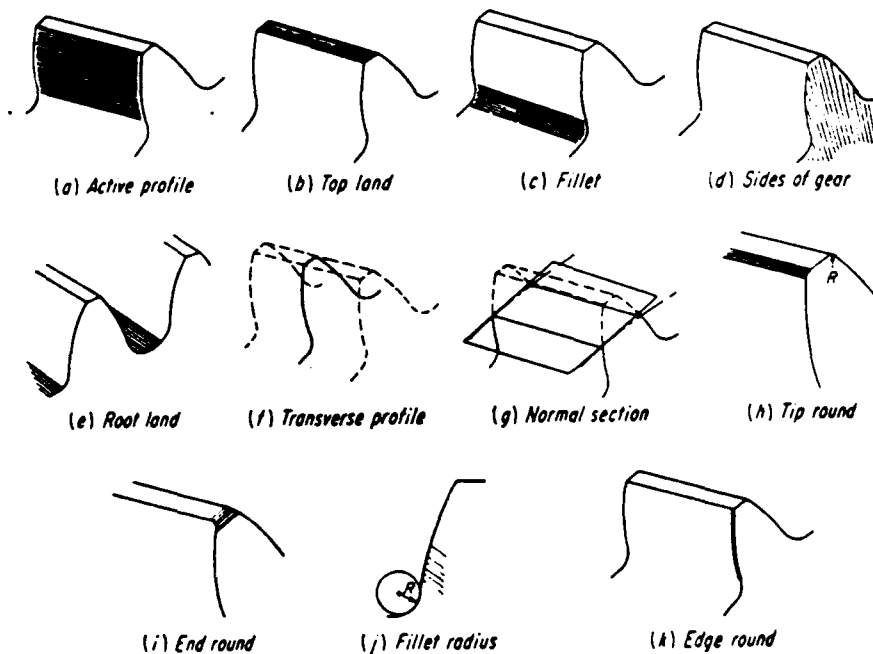


Figure 22. Nomenclature of the areas of contact and boundary zones.

Source: Gear Manufacture and Performance, ASM, 1974.

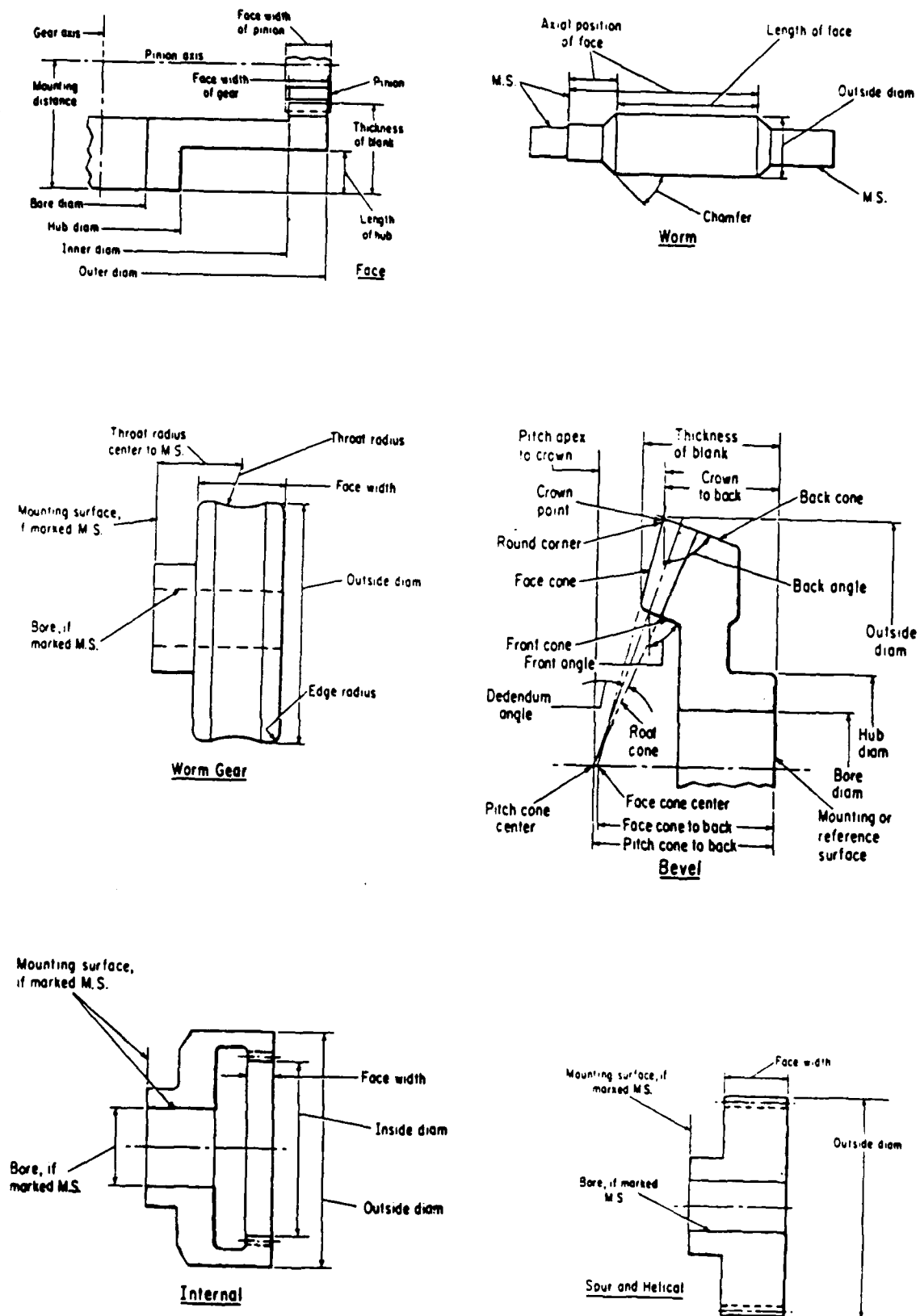


Figure 23. Nomenclature of the elements of gear blanks.

Source: Gear Manufacture and Performance, ASM, 1974.

use for carrying out the manufacturing steps. A general methodology observable in most factories is described below.

**2.2.6.1 Manufacturing of Gears.** Most high-performance gears are steel and are case carburized and hardened. This method of manufacture is the optimum when transmitting power and/or angular motion from one shaft to another. Aerospace gears are usually designed to transmit high power loads at the lowest possible weight with very small safety factors. Thus accurate and consistent manufacture is essential. The normal method of manufacture starts with the steel in the form of a bar or as a forging.

Gear requirements are usually:

- o Sufficient static and fatigue strength to withstand instantaneous and dynamic loads.
- o Adequate toughness to withstand shock loads.
- o Adequate resistance to deformation, pitting, scuffing and wear in the tooth contact area.
- o Resistance to hot oil environments in the temperature range of 100° to 130°C.

In order to meet these stringent demands, transmission components are specified to be case hardened by either carburizing or nitriding. These processes harden the surface of steel parts to improve the wear resistance and fatigue resistance of the gear. When properly heat treated, a residual stress system is set up that causes compressive stresses to exist at the surface further increasing the fatigue resistance. Carburizing is accomplished by diffusing carbon into the surface of the steel gear, usually from a gas atmosphere at temperatures in the range 1650° to 1800°F. Typical carburizing times may be from four to twenty hours depending on the depth of case required. The part must be reheated and quenched in oil to develop a fully hardened surface structure. The quench is a drastic operation and can cause dimensional changes in the part. Often the part is quenched under restraint in a press quenching machine to minimize this type of movement.

Nitriding produces a hard surface by diffusing nitrogen into the surface. This is done at a lower temperature than carburizing at about 1000°F. Diffusion rates are much lower and times of from one to five days are common. Nitriding produces a hard surface by forming hard nitrides in the

case. It does not require quenching, and distortion during heat treatment is minimized. The cases formed are relatively shallow and the process is only suitable for fine pitch teeth gears.

A commonly used steel for carburizing is 9310 but newer steels having greater tempering resistance are coming into use such as CGA 600, Vasco X-2M, Pyrowear 53, or M50NiL. The materials are listed in Table 2.

The steel is initially machined into a blank by a turning operation on equipment that can range from a lathe up to a computer numerical control (CNC) machining center. The tooth forms can then be cut using a process such as milling, hobbing, broaching, or shaping. This completes the soft finishing. Prior to machining the gear blank is carefully annealed to remove all residual stresses and this is the state the gear should be in prior to heat treatment. If there are stresses left, when the gear is heated the stresses will be relieved by movement in the gear. It may be necessary to stress relieve after any heavy machining operation to remove stresses that would adversely affect dimensions later when heated.

The part is then heat treated to produce the desired case depth. Sometimes several carburizing steps are needed when different pitch gears or beaming surfaces are cut on the same component. Carburizing may be done in vertical pit furnaces or in horizontal batch type furnaces. The part is hardened and tempered after carburizing.

The gear is now hard and ready for finishing processes. Basically these processes are needed to compensate for the movement and distortion that is inevitable during heat treatment. It is not desirable to remove too much material at this stage since the case put in by carburizing is now being removed. The traditional means of removing material is by grinding although there are some hard finishing processes which may also be used. Most grinding uses a vitrified wheel which is dressed to the desired tooth form or a cubic boron nitride (CBN) wheel. Finally, the gear is inspected to see if it meets the tolerances desired.

A schematic of these steps is shown in Figure 24.

TABLE 2. CHEMICAL COMPOSITIONS OF CONVENTIONAL  
AND CANDIDATE CARBURIZING STEELS

Material	Nominal Composition											
	C	Mn	P	S	Si	Cu	Cr	Mo	V	Ni	W	Al
9310	0.1	0.55	0.025*	0.025*	0.25	--	1.2	0.12	--	3.3	--	--
CBS 600	0.2	0.45	0.01*	0.02*	1.01	0.11	1.54	0.95	--	0.21	--	0.04
Pyrowear 53	0.1	0.37	0.01*	0.01*	0.98	2.07	1.05	3.30	0.12	2.13	--	--
Vasco X-2M	0.14	0.30	0.03*	0.03*	0.9	--	5.0	4.0	0.45	--	1.35	--
M50 Ni1	0.13	0.55	0.01*	0.01*	0.5	0.2	1.10	4.5	0.35	3.0	--	0.10

\*Maximum permitted amount.

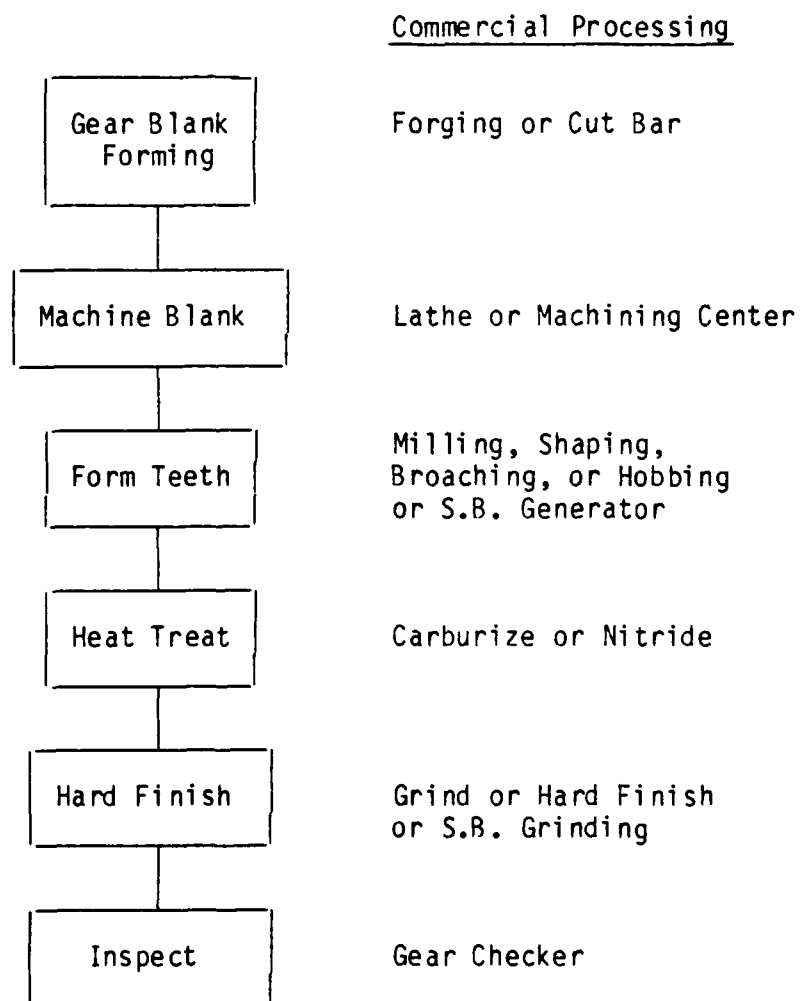


Figure 24. Sequence of gear manufacture.



### Spiral Bevel Gears

While mere conventional machining methods can be used for parallel axis gears, special equipment is needed to produce spiral bevel gears. The usual method used is to calculate the tooth geometry and the corresponding machine settings using gear design and tooth contact analysis software. Both gear members are cut on a Gleason gear generator usually equipped with a modified roll feature which provides maximum control on the tooth contact and compatibility with the grinder. Other models may be used, but the Gleason 26 generator is considered to be the industry standard. The gear member is normally cut by the spread-blade method in which both flanks of the tooth are cut in one setup but the pinion is cut by the fixed setting method with each side or flank requiring a separate setup. This is due to the greater curvature and slot taper on the pinion.

In most aerospace applications, the cut parts are rolled together in a Gleason bevel gear tester and the tooth contact area is observed. Master gears of known quality are used in the test machine to evaluate tooth contact patterns. Gears are run with master pinions and pinions with master gears permitting the production of individual members rather than matched pairs.

The tooth contact pattern is observed at a number of positions, usually designated by "V" and "H" values established by the original equipment manufacturer (OEM) specifications. The test machine operator determines what changes if any are required in the tooth contact pattern size, shape and position, and these are converted to changes in the generator machine settings. The member is then recut to the new settings and the process is repeated, often requiring several iterations to develop the "correct" tooth contact pattern.

The soft tooth cutting development must allow for changes introduced by heat treat distortion, so stock removal during the finishing operation is uniform. It is recommended that 0.005 to 0.008 inch stock per flank for finish grinding be left, while some manufacturers leave 0.015 inch or more to compensate for heat treat distortions. It is not uncommon for a manufacturer to cut two or three parts, send them through heat treat, and check the distortion before cutting the balance of the lot. This, of course, requires additional setups of the gear generator.

The hard grinding, or finishing operation is similar to soft cutting, but with additional complications. Both members are ground on a Gleason 463 or 463A grinder, its predecessor the Gleason 27 grinder, or any one of several earlier models. The spread-blade fixed setting method again is used under normal conditions. Each member is initially ground to summary settings and rolled with a master in a test machine to observe the tooth contact pattern. The same iterative process is used to develop the final tooth contact pattern. It is during the grinding operation that heat treat distortion problems become evident. In the process of developing the tooth contact pattern, the gear flanks must "clean up" while ensuring that stock removal is relatively uniform. If excessive stock is removed at any point on the tooth, the case depth may fall below specifications, which is detrimental to gear performance. Some manufacturers take a series of grinding passes, noting the point at which the wheel first contacts the tooth, i.e., the first spark occurs. By noting how much the wheel is set over in subsequent passes to clean up the tooth, it is possible to determine the maximum difference in case depth on the tooth. It is not uncommon for gears to be scrapped at this point.

The greatest complication in bevel gear grinding lies in the wheel dressing mechanism on the machine. The vernier scales used on the dresser do not lend themselves to accurate and reliable resetting, and the single point diamond wears and changes shape during use. Both of these factors have the effect of constantly changing the geometry of the grinding wheel.

**2.2.6.2 Gear Company Profiles.** A typical profile of the largest gear companies is:

- o \$40,000,000/year gross sales
- o \$1,200,000/year gross profit (3%)
- o 300 employees
- o 7000 active parts, with annual sales of 200 pieces per part. In lot size, there is a definite distinction in supplying prime contractors for new or rebuild programs and supplying spare parts for overhaul purposes.
- o 15% work centers (machine tools) in gear technology
- o 85% work centers in conventional manufacturing technology (turning, milling, drilling, grinding processes).

Larger gear manufacturers often have the capability to assemble gear boxes and also have the necessary stands to test them under load. Most gear makers aspire to be in a position to supply completely assembled and tested gear boxes since this is the highest value added component. Gear box cases are frequently purchased components since the machining centers are usually necessary to produce such components are not available. Gear test cells are expensive to design, construct and install since they must be completely enclosed and capable of testing the assembled box under full load. Sometimes the test equipment is loaned by the customer for the gears. Sometimes there is on-site representation by prime contractors who are important customers of the gear company. Government audit agencies also frequently visit plants producing parts for the defense industry.

**2.2.6.3 Production Difficulties.** Many gear makers experience difficulties in meeting required delivery schedules and lead times of up to 18 months are not uncommon. Some of the reasons that cause delays in production are:

- o Stringent Quality Levels. The aerospace industry is required to maintain documented, certified quality levels which are monitored by the U.S. government. These guaranteed quality levels increase the number of inspections and the requirements for documentation.
- o Dilution of Skill Level. Gears having AGMA precision levels of 12 or higher require a combination of highly skilled labor and adequate equipment. The average age of grinders and generators within the aerospace industry indicates a high reliance on skilled labor. Experienced machinists are retiring from the work force and leaving most gear manufacturers in need of a skilled labor base.
- o Use of Mature Technology. Many gear manufacturers are neither modernizing nor using technologies demonstrated to increase manufacturing productivity, efficiency and quality levels. Examples of techniques available, but generally not in use are:
  - Computerized scheduling systems
  - Efficient flow-type layouts
  - Machine tools equipped with electronics for tool wear detection and tool path control
  - Numerically controlled machine tools
  - Cubic boron nitride (CBN) grinding tools.

**2.2.6.4 Future of the Precision Gear Industry.** As mentioned in the introduction, the precision gear industry is not in a good condition and shows very little sign of improving.

The U.S. Department of Commerce surveys industries and presents statistical data. Standard Industrial Classification (SIC) 3566 for Speed Changers, Drives, and Gears best represents the industry of interest. This industry comprises establishments primarily engaged in the manufacture of speed changes, industrial high-speed drives, and gears. Establishments primarily engaged in the manufacture of these items for motor vehicles are classified in Industry SIC 3714 so are not included in the figures quoted.

Table 3 shows the trend of manufacturing in this industry between 1972 and 1982. There was a decrease in the number of companies as defined by ownership, but an increase in establishments with over 20 employees.

The number of total establishments increased at the same time as the number of larger establishments increased. Even this trend is modest--in 1972 there were 191 establishments with less than 20 employees, while in 1982 there were only 129--a noticeable change--but this industry still has many small companies.

Table 4 shows employee trends in this industry. The number of production workers had been decreasing since 1977. During the same period nonproduction workers decreased at a faster rate. Overall, employment decreased by about 25% in eight years.

Table 5 shows the company sizes in this industry. This industry continues to focus on small business with the median employer having 20 to 49 employees.

Table 6 shows shipments for the states that are most involved in manufacturing these products.

Illinois, Wisconsin, Ohio, and Indiana shipped \$823.1 million in 1982, i.e., over 50 percent of total shipments. These same states have only 32.8 percent of all employment, indicating presumably that the industry in the four states is more efficient than in the other states. At the same time, these four states have only 19 percent of the total establishments with over 20

**TABLE 3. SPEED CHANGERS, DRIVES, AND GEARS (SIC 3566)  
HISTORICAL TRENDS OF ESTABLISHMENTS**

Year	Companies	All Establishments	Establishments With Over 20 Employees
1982	282	307	178
1977	308	327	162
1972	330	346	155

**TABLE 4. SPEED CHANGERS, DRIVES, AND GEARS (SIC 3566)  
HISTORICAL TRENDS OF EMPLOYMENT  
(in 1000)**

Year	All Employees	Production Workers	Other Workers
1985	18.6	12.7	5.9
1984	20.6	13.8	6.8
1982	23.8	15.7	8.1
1977	25.3	17.6	7.7
1972	22.5	15.6	6.9

**TABLE 5. SPEED CHANGERS, DRIVES, AND GEARS (SIC 3566)  
MIX OF COMPANY SIZE - ALL ESTABLISHMENTS**

No. of Employees	All Establishments
1-4	38
5-19	38
10-19	53
20-49	76
50-99	44
100-249	37
250-499	14
500-999	6
2500 or more	1

\*Total reflects those answering inquiries.

**TABLE 6. SPEED CHANGERS, DRIVES AND GEARS (SIC 3566)  
SELECTED STATES - 1982**

	Shipments, \$M	All Employments, 1000s	Establishments With Over 20 Employees
National Total	1621.3	23.8	178
Illinois	252.0	3.7	27
Wisconsin	222.2	3.5	9
Ohio	177.4	2.3	17
Indiana	171.5	2.0	8
Pennsylvania	162.4	2.1	12
Massachusetts	80.6	1.3	11
New York	76.5	1.4	14
New Jersey	69.3	1.0	11
California	40.7	0.7	5

**TABLE 7. SPEED CHANGERS, DRIVES, AND GEARS (SIC 3566)  
FISCAL PERFORMANCE**

Year	Value of Shipments, \$M	Cost of Materials		Cost of Employees		Capital Equipment		End of Year Inventory	
		\$M	%	\$M	%	\$M	%	\$M	%
1985	1434.6								
1984	1426.7								
1983	1298.6								
1982	1621.3	551.1	34.0	499.4	30.8	90.9	5.6	454.8	28.1
1977	1222.3	429.7	35.2	365.4	29.9	48.5	4.0	297.8	24.4
1972	632.7	231.3	36.6	224.2	35.4	21.8	3.4	147.6	23.3

employees. The above data indicate that these four states have the most efficient companies in these industries.

Finally, Table 7 presents the fiscal performance for this industry. Over the 13 years presented, the value of shipments has increased by more than inflation--it increased much faster to 1977, and since 1977 until 1982 has increased at approximately the inflation rate. Since 1982 there has been a decline. Cost of both materials and employees has decreased since 1972. This indicates that overhead costs have increased during the same period. Combined material and labor as a percent of the value of shipment has decreased from 72 percent to less than 65 percent.

This industry's investment in capital equipment as a percent of the value of shipment has increased from 3.4 percent in 1972 to 5.6 percent in 1982. This is above average and indicates that for the period for which figures are available this industry is investing in itself. Over that same period, inventory has increased from 23.3 percent of shipments to 28.1 percent in 1982. For this industry the inventory as a percent of shipments has increased between 1972 and 1982.

The prime contractors who are the precision gear industry's main customers have many complaints about the standards of service they receive from the gear industry. The prime contractors are continually disturbed by the lateness of orders and the slow delivery remains a major concern. Manufacturers are up to six months behind in meeting production orders, even with running two to three shifts and weekends. There is a limited number of suppliers of forgings and castings; and so problems in supply and delivery are common and cause production delays. The available labor pool of skilled machinists is diminishing. Capital equipment is aging and most facilities have not been modernized to take advantage of new technology. Most of the manufacturing processes currently used are time-consuming and subject to a number of quality problems.

The graphs from which these conclusions are drawn represent actual bookings of companies belonging to the AGMA. The data were compiled by the national auditing firm of Deloit, Haskins, and Sells. By superimposing a trend line on these graphs, and projecting it to the year 2000, the result shows a 46 percent reduction in bookings (Figures 25 and 26).

# AGMA CONSOLIDATION

1973 - 1985

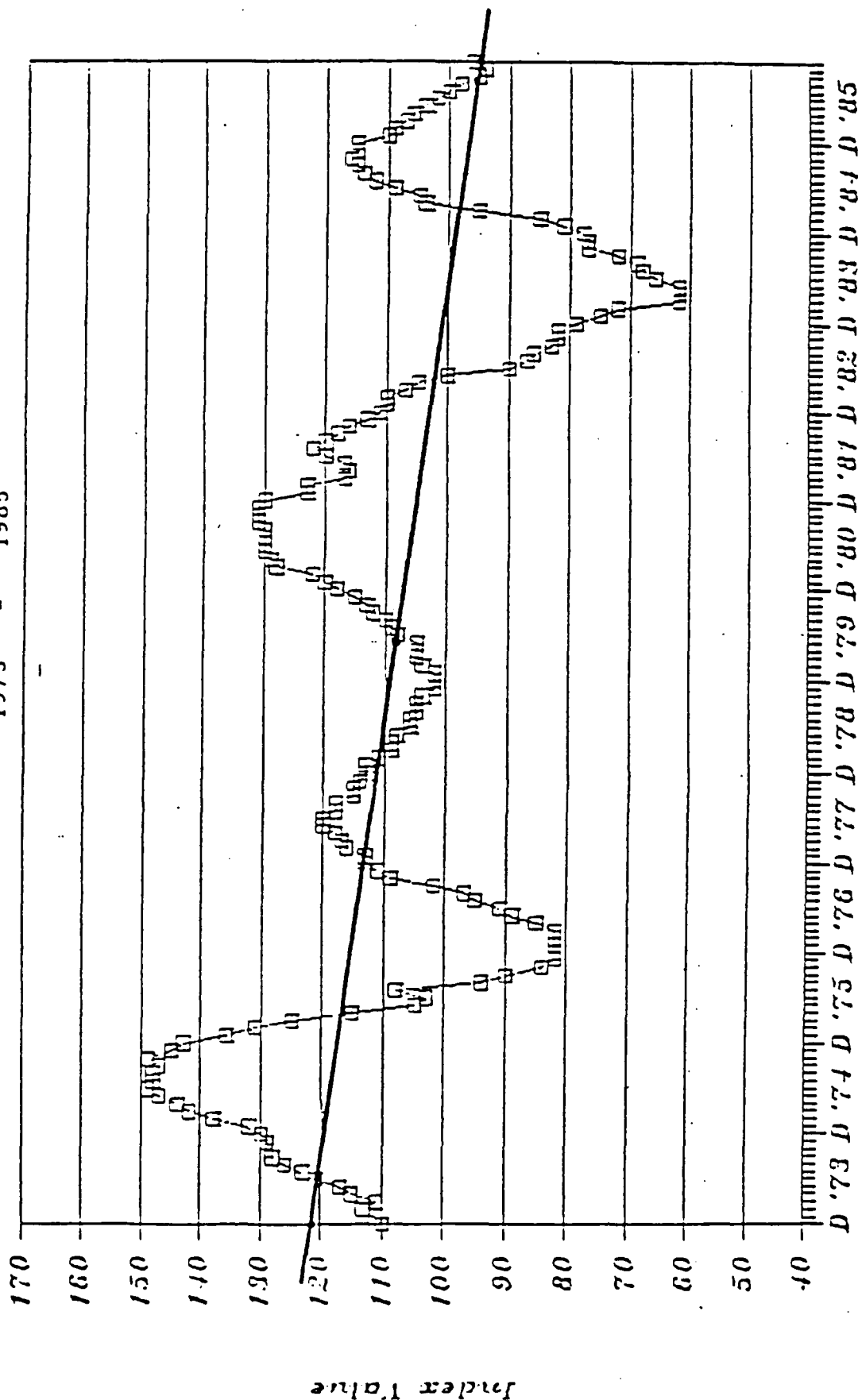


Figure 25. Bookings of AGMA companies showing a decrease in order volume.

Data compiled by Deloit, Haskins & Sells  
for the American Gear Manufacturers Assoc.



# AGMA CONSOLIDATION

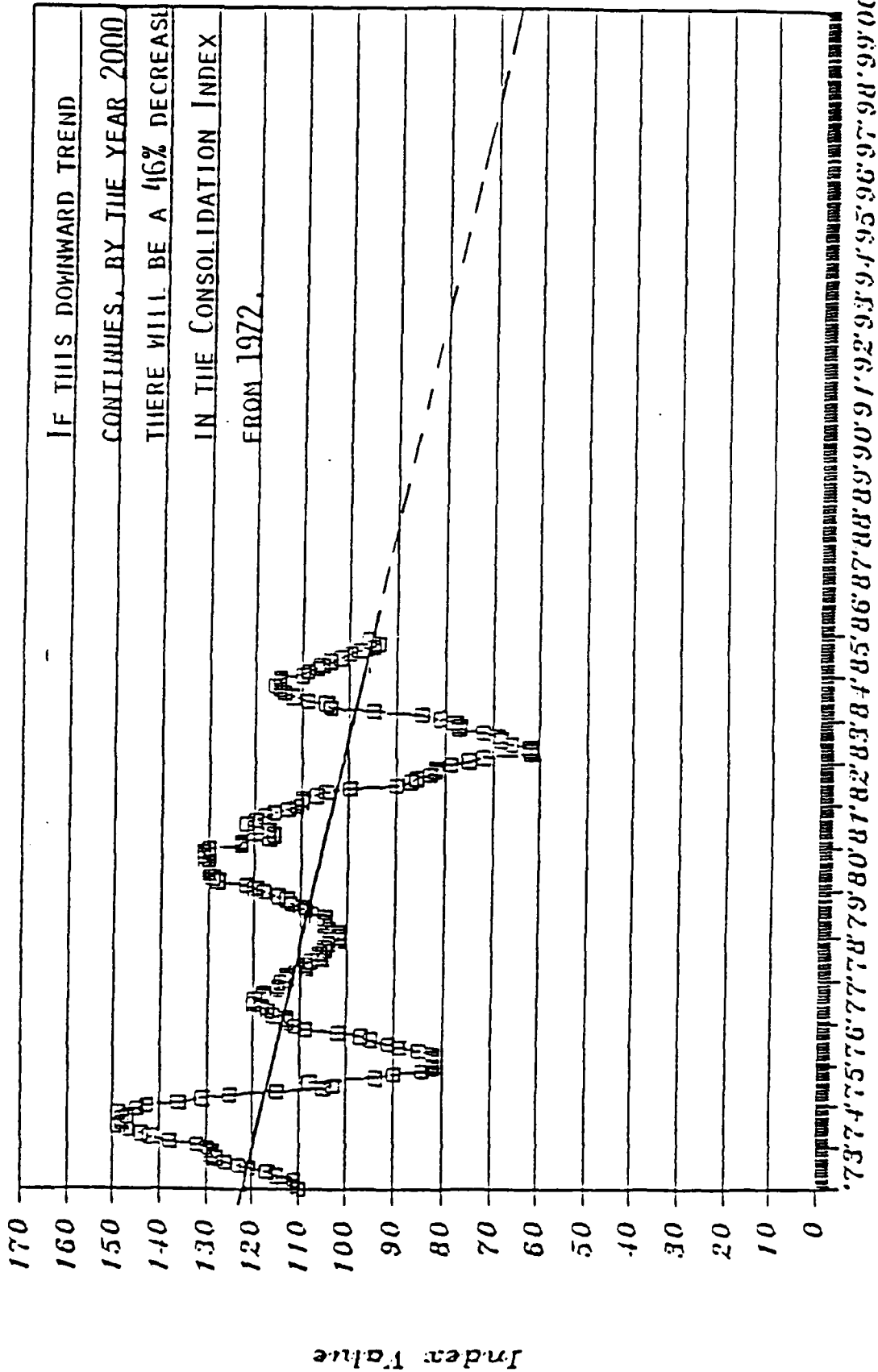


Figure 26. Bookings extrapolated to the year 2000 showing trend of the industry.

Data compiled by Deloit, Haskins & Sells  
for the American Gear Manufacturers Assoc.

The health of the American gear industry has implications that reach further than American jobs. In accordance with this projected erosion, the U.S. Government will be forced to buy gearing systems for military applications from foreign sources. Approximately 25 percent of the gear components used by the Department of Defense are supplied by offshore firms. According to Richard Norment, Executive Director of the AGMA, if the current trend continues (Figure 27), these acquisitions could escalate to over 50 percent. Dependency of this extent on foreign sources will compromise our national security.

At present, rivalry among gear makers is low. Inability to meet current production orders precludes many gear manufacturers from aggressively pursuing new customers although some small gear houses are working hard to attract new business. In addition, the strict manufacturing specifications required by most customers lead to the development of long-term customer relationships between the gear user and the maker. Customers have an incentive to maintain these relationships, as the costs of switching to a rival manufacturer may be high. There is always the tendency to continue with the familiar.

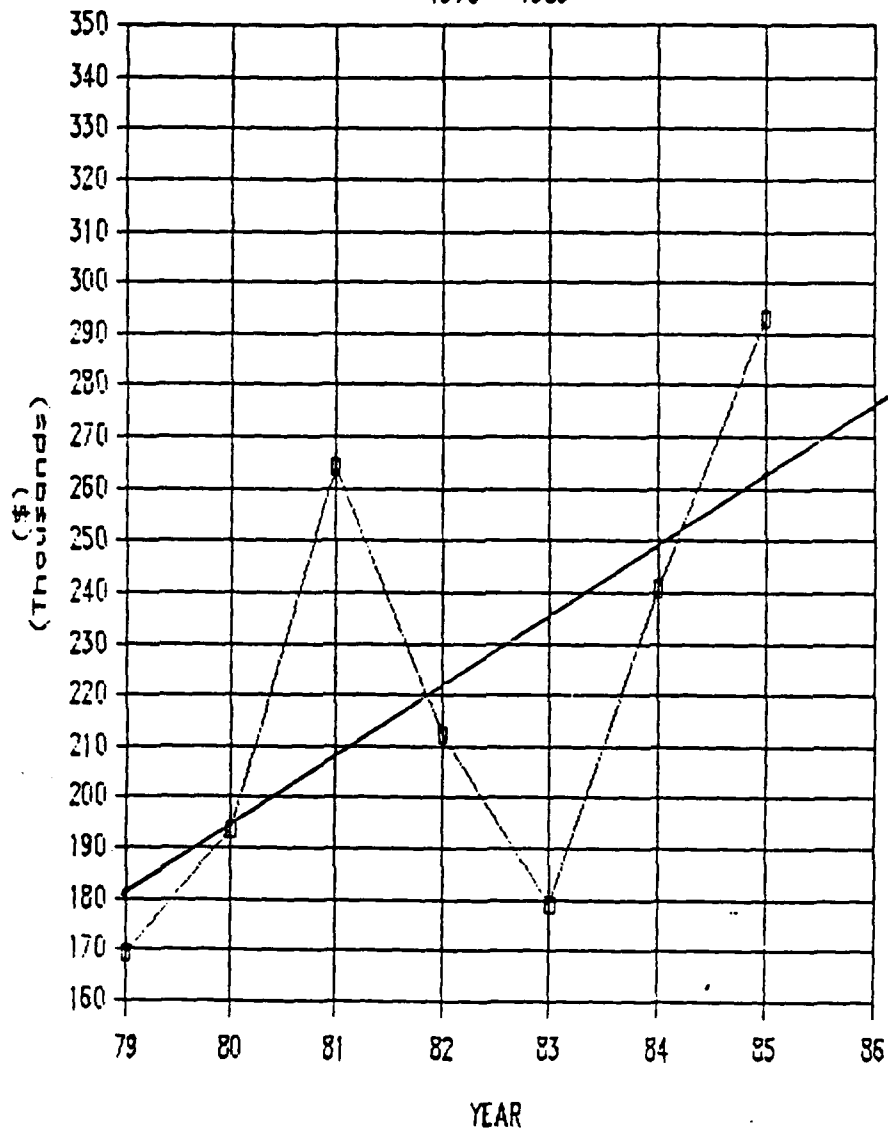
**2.2.6.5 Competitive Position of Gear Users.** Precision gear users have high bargaining power relative to manufacturers. Prime contractors generally place large, long-term purchase orders which comprise a significant portion of a large gear manufacturer's business. Smaller gear manufacturers are often in the loose gear business making small quantities of replacement gears.

Although the costs of changing to a new system are high, gear users have more flexibility in obtaining new precision gear suppliers than manufacturers have in obtaining new customers. Users also have the potential for backward integration (i.e., obtaining ownership or increased control of their supply systems). The larger primes either make part of their own gear needs or are considering doing so.

**2.2.6.6 Competition in the Gear Industry.** There are presently no products available to substitute for precision gears. However, U.S. manufacturers do face a threat from foreign manufacturers imports. However, gear users are motivated by quality, price and delivery, and the United States still retains a slight competitive edge in the technology and manufacture of aircraft and engine components. Imports will constitute a threat as long as

# IMPORTS

1979 - 1985



Data compiled by the United States International Trade Commission/Washington, D.C.

Figure 27. Import increase trend.

U.S. primes have to sign memoranda of understanding and are forced to buy overseas components in order to obtain orders.

The Impact of "Offsets". When an overseas country buys a U.S. weapons system, it is now the custom to negotiate "offsets". These amount to subcontracts, purchase of some local goods (possibly not related to the weapon system being purchased), an investment in local development, or perhaps a plant for local assembly of the weapons. When Boeing sold Airborne Warning and Control System (AWACS) planes to Britain and France, the offsets actually totaled more than the contract value.

While the practice helps the prime contractors export and the DOD is helped by allies using compatible systems ("interoperability"), the offsets have a negative effect on the subcontractors. Work is lost to foreign subcontractors and technology is transferred abroad. Often the foreign companies are placed in a position where they can compete with U.S. industry resulting in imports that the offset system has created. As Paul Freedenberg, the Assistant Commerce Secretary, said, "its not Boeing or General Electric that loses through the offset system. It's the subcontractors that lose."

Offsets are hurting the defense industries that are needed in wartime. They hurt the precision gear industry and the machine tool industry.

The threat of new entrants to the precision gear industry is low. Barriers to entry include high capital equipment costs, extensive manufacturing technology requirements, insufficient availability of skilled labor, and difficulty in establishing a customer base due to the high switching costs involved. In addition, industry growth is high risk as it is dependent on federal funding for military defense projects and renewed growth in the oil industry. (The oil industry is a large user of helicopters for platform work.)

**2.2.6.7 Present Condition of the Precision Gear Industry.** The summary points of the precision gear industry assessment are as follows:

- o Shortfalls in capacity may occur for the large helicopter market in about 1990 when new helicopter types, principally the V22, come into production. Also, new types of propeller fan engines will use precision drive gears. It would be almost impossible to respond quickly to a defense emergency and increased production in a timely fashion.

- o The U.S. aerospace precision gear industry is unattractive to enter because:
  - It is a high risk market which is dependent on military funding and oil prices
  - It does not attract new entrants other than customers who are integrating backward
  - Few manufacturers can attract modernization funds from parent companies because of their minor business impact.

In summary, the precision gear industry is a mature industry which offers little incentive to enter other than the strategic advantages of backward integration.

**2.2.6.8 Availability of Skilled Craftsmen.** The art of manufacturing gears requires not only expensive machinery, but also highly skilled workers who should be considered as craftsmen. It is considered that over 10 years of education and training is required for the average individual in the gear industry. The industry is characterized by generally low volume, highly specialized products, which require this unique and highly educated labor. The industry reports that even on the latest CNC equipment, several years of experience in the gear industry are required for a worker to be able to produce aircraft quality gearing. This may indicate that the CNC equipment is not being used in the optimum way.

The availability of qualified skilled workers in the gear industry is in general decline at a faster rate than the decline in orders, as fewer new entries into the work force find their career objectives on the shop floor. Simultaneously, with the negative global economic factors, gear companies are finding it increasingly difficult to keep their remaining skilled workers employed.

The problem is not limited to blue-collar workers. There is an increasing problem finding qualified design and manufacturing engineers for the gear industry.

All the companies visited reported that a serious labor shortage is developing for skilled machinists in the gear industry. This factor in itself is an inducement for manufacturers to move operations to foreign nations where

workers are more plentiful. This shortage diminishes the chances that the United States could respond quickly to an emergency situation.

One problem is that manufacturing has a poor image in the high schools where graduates tend to avoid factory work or continue on to obtain manufacturing degrees. Most people regard manufacturing as unexciting, not leading to interesting careers. Another perception is that the work of the defense industry and its subcontractors is cyclic, leading to layoffs when the government reduces funding. People require more security and seem to prefer jobs in the service industry as being cleaner, more comfortable, and lucrative.

Due to economic conditions, U.S. apprenticeship programs have dwindled sharply, limiting the pool of potential employees. The cutbacks are partly due to corporate cost cutting and partly because of some unions' attempts to preserve the jobs of existing members by reducing the number of trainees. The Machinists Union estimates that apprenticeship spots have dwindled 45 percent to 12,000 in the past five years.

Yet manufacturing companies can no longer depend on older workers to train younger replacements, as they once did when craft jobs were passed from father to son. Although the shortage of skilled blue-collar workers is greatest in white-collar cities such as Stamford, Connecticut, and Boston, Massachusetts--where more than 70 percent of high school seniors enter college--young people are shunning factory jobs even in traditionally blue-collar cities such as Pittsburgh, Pennsylvania, St. Louis, Missouri, and Detroit, Michigan. There is a feeling among younger workers that factory jobs are dirty and boring.

Companies, in turn, complain of a growing mismatch between the jobs they are trying to fill and workers' skills. They say many job applicants cannot pass reading and math tests to qualify for apprentice positions. In the past, poor academic skills did not automatically ruin an applicant's chances, but as manufacturing becomes more sophisticated, workers are running numerically controlled computer equipment requiring an understanding of math.

#### **2.2.6.9 Management Shortcomings Within the U.S. Precision Gear Industry.**

Inability to meet modern delivery schedules and quality problems faced by current gear manufacturers are caused by the following practices:

- o Reluctance to invest in automated equipment has resulted in increased dependence on skilled labor and longer processing times
- o Excessive work-in-progress (WIP) and manual off-line inspection procedures have resulted in increased damage due to handling
- o Reluctance to change operating procedures by employing new technologies and processes has resulted in inefficient machine utilization and low production rates
- o Minimum preventive maintenance has resulted in delays in detecting machine inefficiencies, worn tooling, and higher scrap levels.

The lessons learned from the study of existing plants would suggest that the following measures be implemented:

- o Avoid the inherent inefficiencies of the job shop environment by managing the gear business as a backward integration of the assembly line.
- o Develop and maintain employee skill levels with an adequate company supported training and continuing education program for direct and indirect labor.
- o Regularly schedule equipment preventive maintenance enforced by a qualified maintenance staff.
- o Set capital equipment budgets at sufficient levels to implement and maintain a state of the art manufacturing process.
- o Establish solid relationships with casting and forging suppliers and work toward just-in-time delivery.
- o Strive toward minimum material handling and maximum in-process inspection.
- o Standardize gear process plans and schedule production to run higher volume part families.
- o Utilize group technology in part make/buy decisions and plant layout.
- o Support gear manufacturing research in order to improve processing by improving quality and reducing cost.

### 2.2.7 European Gear and Machine Tool Companies

Of the gear companies visited, only Westland and possibly Watteum could be classified as a precision gear maker. Westland makes gears for its own line of helicopters and for U.S. and European companies. Westland is partly owned by Sikorsky. The other gear makers were mainly suppliers to the automotive and heavy construction industry.

Most of the machine tool builders visited are famous names, often seen in this country covering all phases of gear manufacturing except perhaps for machining centers for blank preparation. Most of the companies go back 100 to 200 years and started with the industrial revolution making hand tools. As industry developed needs, they filled them and sometimes created them. The latest phase of development is CNC and this is still less than 10 years old in the gear industry. Most companies are experiencing business difficulties as manufacturing is lost to third world countries and there is a reduction in needs for manufacturing in Europe. However, the companies are attempting to sell in the third world, but often there is a problem because of the relatively high cost of new, particularly CNC equipment. Third world manufacturers would rather buy used equipment and train the necessary manpower to use it, thus combining low equipment costs with low labor rates.

However, with all these difficulties, the European machine tool companies are here to stay and are aggressively chasing the U.S. market for orders, even though the declining value of the dollar makes sales more difficult and profit margins less. European companies are more likely to be run by technical people than by accountants and this reflects in the business strategies. They do not have the usual MBA view that the next period profit is the only concern but plan more for the future. One example of this was the almost universal apprenticeship schemes in use to train the core of the work force in machine use. Such schemes are slow to pay off but result in a reliable, well-trained work force.

One German machine tool company has a sales manager with an engineering PhD, which would be unusual in the United States. This type of attention to sales may have prevented more sales losses than might have been anticipated. Two years ago, the dollar peaked at 3.47 marks and now it is worth less than half that value. It might be expected that German machine tools would be



priced out of the market but, in fact, German exports have not fallen in actual volume. The majority of German exporters expect exports to rise. The dollar's slide has merely lowered the growth rate in exports. Companies have increased prices slightly, reduced profit margins, improved warranties, but most of all, sold the idea of quality. Most users perceive German machine tools as being of higher quality than American tools and often of performing better. Their goods are at the top of the market and frequently command a higher price. They firmly occupy strategic niches in the market and are difficult to dislodge. The machine tool builders are backed by the German Technological Universities such as Aachen and there is a close relationship (often referred to in the U.S. as the Aachen Mafia!) which means that the machine tool industry rarely makes mistakes.

There is a strong nationalistic instinct in the industry. It is rare to see foreign machines in German factories--even Japanese machining centers. The exception is Gleason equipment because the U.S. Gleason Works has always had a near monopoly on spiral bevel manufacturing tools. The Germans complain that Gleason is slow introducing CNC and already there is a fledgling German company (Weiner Gear Technology, Inc.) which is moving fast to challenge Gleason SB grinders and has already sold eight machines this year. Five U.S. companies--all in the aerospace industry--are interested in these machines.

The author's observations are that there is nothing magic about German technology and that the Americans could do as well or better with proper application and financing of talent. The perception that U.S. machine tools are poorly conceived, tested, and backed with slow and indifferent service, must be countered and confidence restored. There is no doubt that both the American and German machine tool industries are undergoing difficult times. The U.S. machine tool industry needs technical and financial help along with time to regain a little of its former position as a world class industry. The development of the National Center for Manufacturing Science with headquarters in Ann Arbor, Michigan, formed to sponsor research projects addressing basic (generic) problems in manufacturing is a good start.

#### **2.2.8 German University/Industry Involvement**

Two universities were visited at Munich and Aachen. Both these organizations work closely with the gear industry in providing research and staff to

ensure that German industry retains its position at the leading edge of technology. Nothing like these organizations exists in the United States, so they are worth describing in some detail. These descriptions are contained in Appendixes A and B.

#### **2.2.9 AGMA Gear Exposition and 1987 Fall Technical Meeting**

AGMA is making strenuous efforts to maintain a healthy gear and particularly precision gear industry in the United States. The Gear Exposition and Fall Technical Meeting held October 4-7, 1987 at the Cincinnati, Ohio, Convention Center were aimed at informing attendees as to the latest in gearmaking technology and supplies and to give a feel for the gear-related research that is available to help improve their products.

This exposition was the first real show of available equipment and services dedicated to the gear industry. At the 1986 Fall Meeting, there were tabletop displays but planning started immediately on an Exposition to be held in Cincinnati, Ohio, in 1987. Further shows would be held at two-year intervals to alternate with the International Machine Tool Show.

The show had 64 exhibitors on a floor area of about 25,000 sq ft. About 40 of the exhibitors were AGMA members. Twenty-five percent of the exhibitors were makers of machine tools, and only four of these were American companies not relying on major parts built overseas. These four were Bryant, Fellows, Gleason, and National Broach.

They were all showing CNC equipment capable of being installed in a computer-controlled factory (maybe of the future!). The overseas makers all showed excellent equipment well suited to high production gear manufacture. Only one machine exhibitor was from Japan (Mitsubishi), although Perez offered Okamoto equipment, the rest being European. A Chinese exhibitor failed to appear due to visa difficulties. There is a tendency for the overseas producers to gradually buy the American machine tool companies, the latest example being part of Barber-Colman of Rockford, Illinois, being purchased by Pfauter-Maag of Zurich.

The second biggest category was gear makers represented by eleven manufacturers covering all categories of gear types from plastic to aerospace. Eight exhibitors showed tooling and accessories with some makers showing hard

finishing tools using CBN and also titanium nitride coatings. Eight-exhibitors showed gear measuring equipment most having CNC models available. Three of the seven were U.S. makers. An interesting trend was that one U.S. machine tool maker (Gleason) was showing Hofler (German) measuring equipment. Five exhibitors showed heat treatment services with emphasis on induction hardening of gear teeth. It was noticeable that apart from an exhibition showing fluidized bed treatments there were no manufacturers of conventional heat treatment equipment, as might be used to produce carburized cases. At least two exhibitors were offering computer software for gear design.

The show was considered successful by the majority of exhibitors and over 1300 people attended. The exhibitors liked the high quality of attendees with very little waste of exhibitor's time as usually occurs at some of the bigger, less focused shows. It was suggested that longer hours would help persuade exhibitors to bring more working hardware for future shows.

The fall technical meeting was attended by about 300 people who heard 16 papers over two days. There were four technical sessions including (1) Design and Rating, (2) Measurement and Control of Transmission Errors, (3) Wear and Materials, and (4) Manufacturing Technology. Four papers were by authors from Europe. The AGMA is to be congratulated on organizing a very successful conference which will help make the gear industry aware of developments that will improve competitiveness and productivity. The next combined Expo and Fall Technical Meeting will be in Pittsburgh, Pennsylvania (1989).

#### **2.2.10 International Gear Research**

According to a survey presented to ASME Gear Research Institute members at the 1987 annual meeting held on March 6, 1987, more research is being done overseas than in the United States. This is a summary of all work associated with gears and from the American experience, it is probable that manufacturing technology accounts for a very small proportion of the whole. The amount of research conducted in the major countries is summarized below in Table 8.

Gear research conducted in Germany is a co-venture activity among the gear industry, the universities and the government. In 1985, \$3.8 million was spent on gear research, primarily at Munich and Aachen, although there are 40 different centers throughout the country. The results of the work are given to only German sponsoring companies. Currently there are approximately 100

TABLE 8. 1985 OVERSEAS GEAR RESEARCH

Country	Amount, \$ Millions
Japan	5
Germany	3.8
France	1.5

projects under way in Germany in various areas of gear research, under the surveillance of the Forschungsvereinigung Antriebstechnik (FVA). The various research groups must compete for the research contracts which are awarded on the basis of competency, past performance, and delivery date for the information.

In France, gear research is conducted through Centre d'Etudes Techniques des Industries Mecaniques (CETIM) which is a nonprofit, public organization dedicated to promoting technological progress in the mechanical engineering industry. In 1985, approximately \$1.5 million was spent for gear research at several locations in France.

In the United Kingdom work is being conducted on a limited basis at several universities throughout the country. The British Gear Manufacturers' Association (BGMA) and the Institute of Mechanical Engineers (IMechE) have recently jointly established the British Gear Association (BGA). Within the BGA is the Gear Research Council, whose mission is to direct gear research and development on behalf of industry. A recent survey concluded that the British gear industry had fallen behind other international competitors in the design, manufacture and inspection of gears. To fund gear research, the BGA has committed themselves to raise \$400,000 in 1987 building up to \$1.3 million in six years.

Japan is the center of gear research in Asia. From the titles of the papers written in Japan, it appears that the thrust of their research is toward industry. After visiting Japan, Darle Dudley concluded that 50 percent of the world's gear research is conducted in Japan. If this is true, then the equivalent of \$5 million would have been spent in 1985.

### **2.2.11 Ongoing Manufacturing Technology Research Programs for Gears in the United States**

The following government agencies were contacted for details on gear manufacturing programs:

Air Force	- Wright-Patterson AFB, Ohio
Army	- AVSCOM, St. Louis, Missouri - Fort Eustis, Virginia - Watertown Arsenal, Massachusetts - Rock Island, Illinois - Warren, Michigan
Navy	- Sea Systems Command, Washington, DC - Naval Air Engineering Center, Lakehurst, NJ
Department of Commerce	- Washington, DC
Bureau of Mines	- Washington, DC
NASA	- Lewis Research Center, Cleveland, OH

In addition, nongovernment sources were contacted, plus 37 universities were contacted who had academic membership in AGMA.

The most significant sources of research are:

ASME Gear Research Institute, Naperville, IL  
Ohio State Gear Dynamics and Noise Research Laboratory, Columbus, OH

In general, it was found that more work was being done on design and lubrication of gears than in the manufacturing area. The most significant research programs were as follows.

**2.2.11.1 Wright-Patterson Air Force Base.** The main manufacturing activity in the gear area is a Technical Modernization (Tech Mod) program initiated through General Electric.

Tech Mod is sometimes referred to as industrial modernization incentives programs (IMIP). There are three phases of development for a Tech Mod project. They are:

- o Phase I is a "top-down factory analysis" which both evaluates the needs of the overall facility and identifies candidate manufacturing technologies/modernization opportunities which are applicable to the types of systems produced in the facility. At the culmination of Phase I is a negotiated "business deal" between DLA and the contractor. Considerations include incentives, benefit sharing arrangements, mutual investments, applicable technologies, and return-on-investment hurdles.

- o Phase II is the development of the enabling technologies and the design and fabrication of factory modernization enhancements. Phase II also identifies implementation plans, specifies hardware/software operational requirements and validates specific applications through method demonstrations.
- o Phase III is implementation of the Tech Mod project, including contractor purchase and installation of capital equipment to implement those Phase II candidates that demonstrate the highest potential payback and other "off the shelf" equipment to be used in the overall plant modernization.

The whole Tech Mod/IMIP procedure is summarized in Figures 28 to 32.

A Phase I program has been completed by Western Gear and a detailed study report issued. A Phase II proposal was submitted and was rejected. However, this program is now being reconsidered. A Phase I proposal has been submitted by Aircraft Gear but so far has not been accepted.

**2.2.11.2 AVSCOM-St. Louis/NASA-LRC.** An important ManTech program is ongoing and consists of making modifications to a 463 Gleason spiral bevel grinding machine. The program is funded by AVSCOM with the contracting arrangements by NASA-Lewis Research Center. The contractor is Bell with Gleason Works as the subcontractor. Most of the axes of the machine, including dressing, are intended for CNC control. Controls of this type are essential if a spiral bevel grinder is to be included in an FMS. On completion of the machine, it will be tested at Bell on aerospace gears. Completion of the contract is expected in September 1988 when an industry review will be held.

An important program is being developed to design and build a Super Gear Center. This program is being carried out by Lycoming Textron with the assistance of Brigham Young University. A factory design system has been developed which will be used to test the design of the Super Gear Center. The factory will be designed using group technology principles, but will not be a full FMS in the first instance.

A smaller program completed this year was to install a CNC Zeiss coordinate measurement machine at Sikorsky for gear checking. The use of CNC coordinate information in testing and alternatively machine control was reported.

## TECH MOD/IMIP IS:

- o A MUTUAL AGREEMENT
  - D.O.D. AND PRIME CONTRACTORS
  - D.O.D. AND SUB CONTRACTORS
  - PRIME CONTRACTORS AND SUB CONTRACTORS
- o TO PRODUCE LOWER COST WEAPON SYSTEMS
  - COST REDUCTIONS
  - IMPROVED SURGE CAPABILITIES
  - IMPROVED CONTRACTOR RELIABILITY
  - IMPROVED MANUFACTURING TECHNIQUES
- o THROUGH A MUTUAL SHARING
  - RISK
  - INVESTMENT (ENABLING TECHNOLOGY)
  - SAVINGS

*Figure 28. Tech Mod/IMIP.*

## IMIP/TECH MOD PHASES

- PHASE 0 - PHASE I SCOPING PROPOSAL
- PHASE I -
  - "AS-IS" NEEDS ANALYSIS
  - COMPANY EXTERNAL ANALYSIS
  - "TO-BE" CONCEPTUAL PROJECT DESIGNS
- PHASE II -
  - "TO-BE" DETAIL DESIGNS
  - RESOURCE REQUIREMENTS
  - IMPLEMENTATION PLAN
- PHASE III - IMPLEMENTATION AND VERIFICATION

*Figure 29. IMIP/Tech Mod phases.*

Source: Western Gear

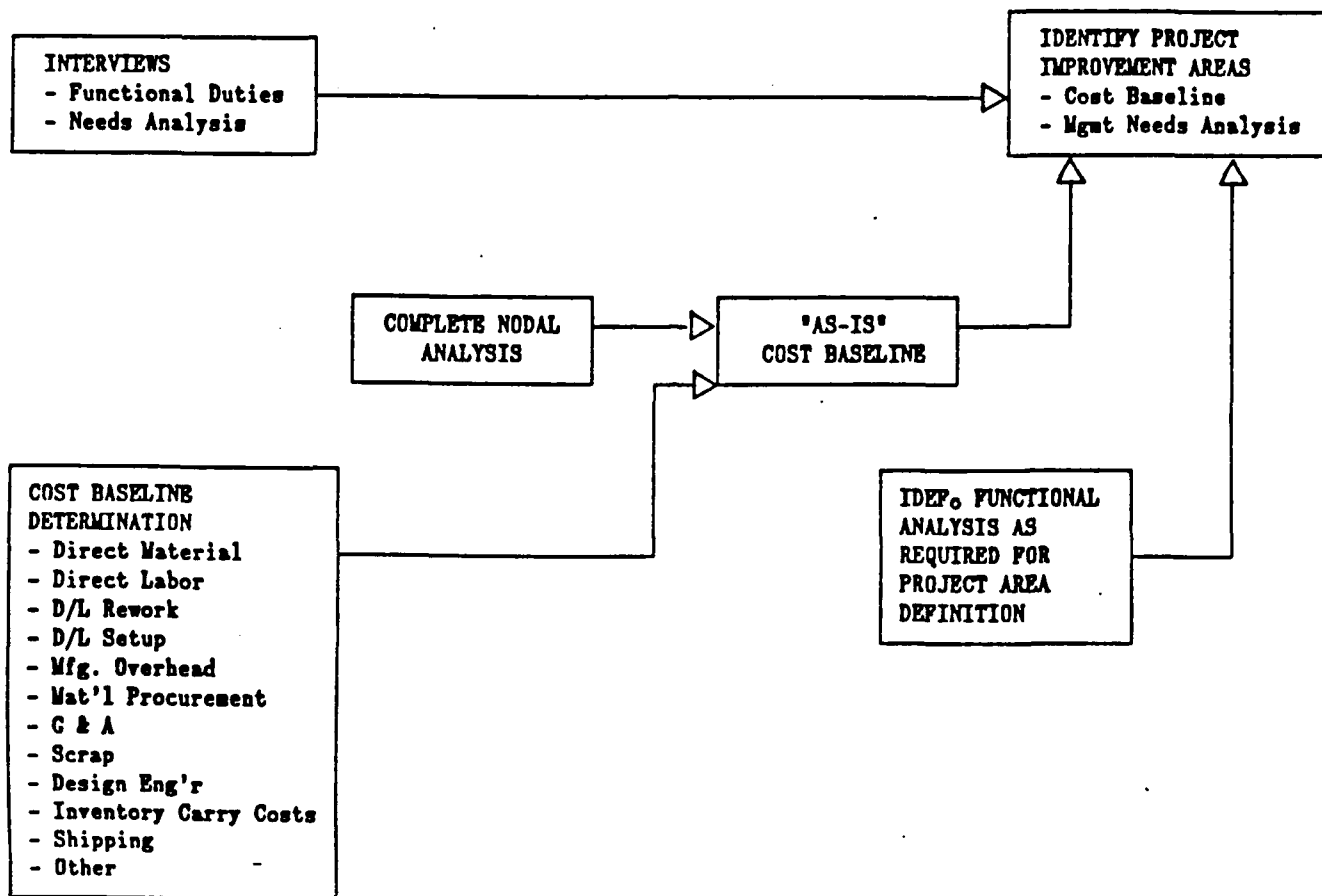


Figure 30. Factory analysis Phase 1.1, "as-is" analysis.

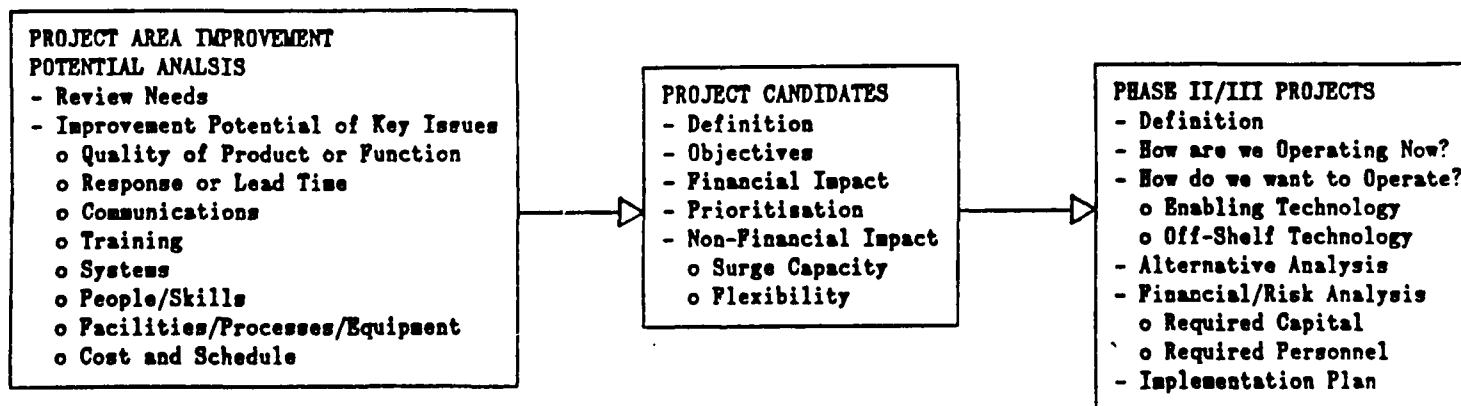


Figure 31. Factory analysis Phase 1.2, "to-be" analysis.

Source: Western Gear



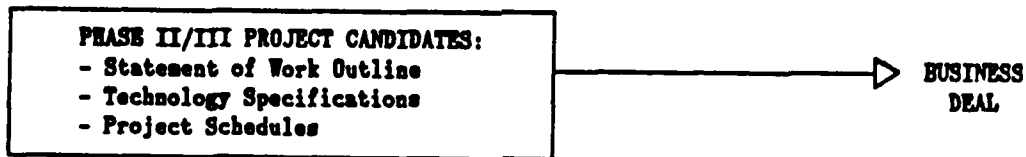


Figure 32. Factory analysis Phase 1.3, Phase II and III strategy.

**2.2.11.3 Fort Eustis.** Fort Eustis has a program with Garrett on the laser hardening of a helicopter gear. Work started with a 1.2 kW laser and later was continued with a 5 kW machine, for which the process parameters are being established. It is hoped that an adequate case hardness pattern can be determined using a single-beam scanning technique, although the geometry is complex and there are some problems with reflections. It has been established that a material called L6 (0.66C, 0.34 Mn, 1.0Co, 1.7Ni) appears optimum for laser response. The work will conclude with single-tooth bending tests and pitting and scoring evaluation and is scheduled for completion in October 1988.

A parallel effort in induction hardening may be undertaken by Allison who will harden an idler gear for the T63 engine. These gears will be tested in an actual engine by arrangements with Naval Air Propulsion.

Some work on high hot hardness steels suitable for gears is being carried out with the Air Force by General Electric to evaluate the fracture toughness of X53, Vasco X2M, CBS 1000, CBS 600, and M50 NIL. This work is scheduled for completion in mid-1988.

**2.2.11.4 Navy.** Some preliminary work on Ausrolling gears has been done on materials including 9310 by Penn State University. The process was originally developed by International Harvester before the IH research laboratories were closed. The gear shapes are precarburized and roll-swaged to what is hoped to be a net shape. The Naval Air Systems Command, Washington, DC, is interested in pursuing fund this program with the objective of building a double die machine having actual production capability. There is interest in the process by industrial gear producers, both aerospace and automotive.

**2.2.11.5 Department of Commerce.** The Department of Commerce is providing about half the funding for a program on austempered ductile iron (ADI). The contractor is the Gear Research Institute who is obtaining the remaining funding from industrial sources. The program is now in its third year and a data base is being developed for the use of ADI in gear and other critical applications. Test gears and other test pieces are being made and subjected to mechanical testing, contact fatigue, and wear. Near net shape forming is being considered, also the use of ADI for quiet precision gears. The program is scheduled for completion in June 1988.

**2.2.11.6 ASME Gear Research Institute (GRI).** The GRI is a small organization occupying space owned by Packer Engineering in Naperville, Illinois. Although their facilities are restricted, they have many industry contacts and serve as a "clearinghouse" for research. They act as contractor for two of the government agencies mentioned above and are working on a variety of concepts, some of which may be related to precision gear manufacturing. These concepts include:

Combining net or near net shape forming with a low-distortion heat treat procedure which can produce microstructures in ferrous alloys having high performance capabilities. Hard precision finishing is also an area of study.

Parallel concepts proceed toward two objectives. The first objective is to demonstrate the feasibility and advantage of precision net-shape gears made from austempered high carbon steel, one version of which will include a superplastic ultra high carbon (UHC) steel).

Considerable interest in austempered ductile iron (ADI) as a gear material has developed. ADI gives a uniquely favorable performance, i.e., strength and toughness, due to the unique microstructure developed by austempering. This structure can also be developed in certain steel compositions and, when done, should provide superior performance, highly competitive with and potentially surpassing that of carburized steel.

**2.2.11.7 Ohio State University (OSU).** Gear Dynamics and Gear Noise Research Laboratory. In 1980, the OSU Department of Mechanical Engineering established The Gear Dynamics and Gear Noise Laboratory as a research consortium funded by industry. The Laboratory's main goal is to advance the state of the art of gear design through research aimed at developing a better under-

standing of gear dynamics and gear noise. The scope of this research ranges from the development of computer software to the acquiring of experimental data from gear test stands. Most funds received by the laboratory are used to provide financial aid for MS and PhD students working on thesis projects related to gearing. Sponsors meet with faculty and students twice yearly to review research progress and to discuss research goals of the laboratory.

Recently a National Science Foundation--Engineering Research Center (NSF-ERC) for net shape manufacturing was established at OSU. This Center will be funded by NSF at \$9.7 million over a five-year period, and this amount is pledged to be matched by industry. This Center will be a cooperative activity by NSF and industry and the University and is expected to become a national resource to improve U.S. international competition in manufactured goods by providing manufacturing techniques which result in minimal secondary machining (e.g., net shape).

An important aspect of the research of the Center will be in improving the processes used to net shape manufacture gears. Since industry participation is vital to the success of this program, they are requesting help and guidance from industry so that research is directed toward relevant manufacturing problems which would benefit the gear manufacturing community.

Typical programs include the development of a four-axis CNC T.10 Cincinnati Milacron machining center to produce prototype gears with a single tool or with a roughing and a finishing tool. Gear measurement is under study as is near net shape technology involving investment castings, spiral bevel forging, and orbital forging. Fatigue tests are being conducted to compare extruded gears with conventional products.

### **3. MANUFACTURING TECHNOLOGY RESEARCH NEEDS**

The precision gear industry will not introduce new gear manufacturing technology on the factory floor at a rate that will make a significant change to the industry unless substantial help is obtained from outside. The industry simply cannot afford to make large investments of the type needed. New CNC machine tools can cost from \$0.2 million to about \$1 million and so investments must be made carefully with the assurance that the work will be forthcoming to keep the new machine busy. Often the situation is that the machine will not be obtained unless the orders are received and the orders will not be placed because the machine is not available. A system of reducing the risk of introducing new technology is necessary so that precision gear plants will install advanced manufacturing technology. If this is done, it should improve gear manufacturing and stop the loss of gear orders to overseas makers and to ensure prompt completion of existing orders.

The best way to introduce new manufacturing technology in the gear industry is to demonstrate it in a fully operational working environment. This involves building a working state of the art factory. In this setting an individual company could try the new technology with no risk and little investment. Based on this experience, they would be able to invest appropriately with a considerably reduced risk.

#### **3.1 DEMONSTRATION GEAR FACTORY**

The gear plant of the future should be equipped with automated, in-process inspection equipment that constantly monitors gears during all stages of production and provides feedback to correct the process so that only good parts are made. To do this the plant would be highly instrumented with sensors and could be regarded as an instrumented factory (INFAC). Post-processing inspection is an attempt to find the bad parts that should not have been made in the first place. In-process inspection should enable constant corrections to be made through the CNC controller to ensure that machining operations are being performed within the tolerance band allowed by the gear designer.

### **3.1.1 Factors Influencing Manufacturing**

We live in exciting times when manufacturing is in a period of rapid change and the rate of change is accelerating. It will soon become true that if you use yesterday's manufacturing technology to make the part of today, you will be out of business tomorrow. Many of today's gear shops have equipment with an average age of 25 to 40 years, which is older than many of the operators using the machines.

There are many factors which are impacting manufacturing. Some of the key drivers causing change are listed below.

- o Quality: Consumers are becoming more critical of quality, but the primary pressure here is coming from industrial customers. A vendor who does not regularly and reliably deliver a quality product will not be a vendor. Gear makers must produce quality parts on time if their customer is to meet a schedule.
- o Inventories: Inventory reduction has proved much more difficult than most managers originally visualized, but this nevertheless must remain an important criterion. Most gear plants are characterized by the amount of work in progress (WIP) lying around the factory. U.S. industry, at least, has been based on "push", i.e., pressuring each department to produce as much as they can and rewarding them for the quantities produced independent of whether anyone needs the output. In a "pull" system, product is made only to the extent that there is a need for it downstream. The transition from push to pull has been very difficult since it is contrary to most existing reward systems. If a gear company is producing ship-sets or gear boxes all the required components should arrive at the assembly point in sequence.
- o Competition: More often manufacturers of gear products, however specialized, compete locally or some place else in the world. Each and every company must act as if there is a clear, well financed competitor trying to get their business--if there is not one today, there will be one tomorrow and the company that is not prepared will die. A company in Chicago, Illinois, that cannot compete with one in Ohio or Italy is operating at risk.
- o Cost: This may be another way of considering competition but, with other factors being equivalent, price will be the determiner.

- o Flexibility: Changes in design, quantities desired and delivery dates must all become standard operating procedures (SOP). Customers will no longer settle for schedules based on the convenience of the vendors. A customer concerned with inventory will not be willing to commit to the 12-month order quantities. JIT will become a way of life.
- o Integration: Based on many of the drivers listed above, there will be pressures for integration of manufacturing. By this it is meant performing more operations at a single site. For example, heat treatment, plating and gear box assembly give a manufacturer more control over his destiny.

### 3.1.2 Gear Manufacturing Overview

Manufacturing is the process by which material, labor, energy, and equipment are brought together to produce a product having a greater value than the sum of the input. This can be shown as a system as indicated in Figure 33. Here the input is indicated as material, labor, energy, and capital. The capital input provides the equipment and facilities required for combining the material labor and energy. Output includes product but there is always some undesirable output--waste and scrap which should not be forgotten. Also as indicated for the system shown in Figure 33 there are external influences that

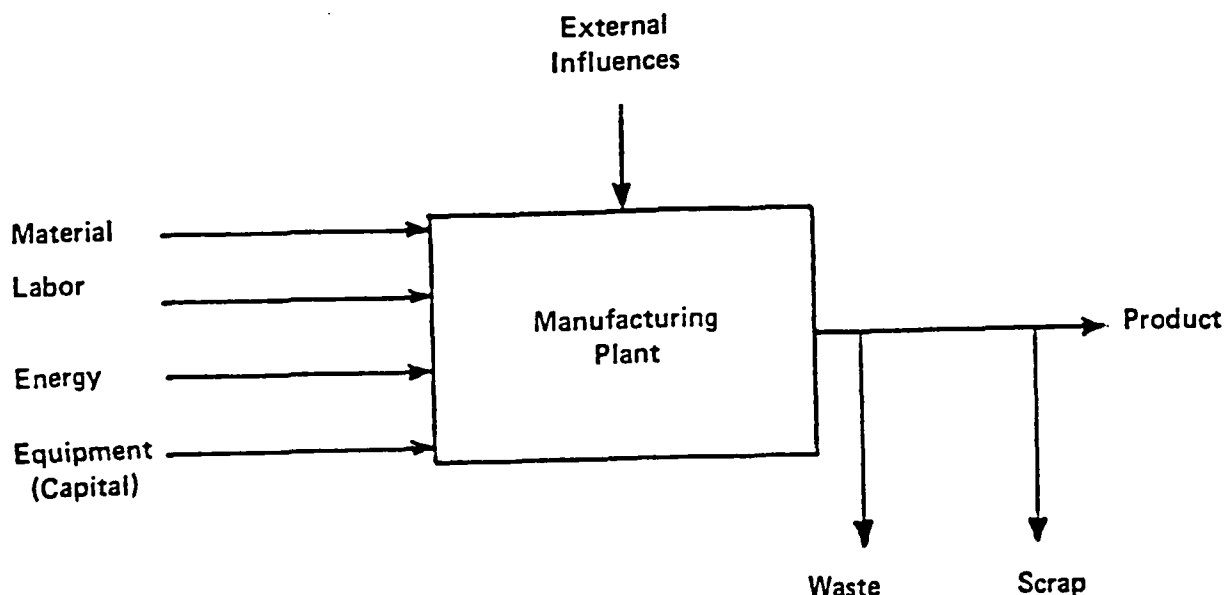


Figure 33. A manufacturing system.

should not be ignored. External influences can include government actions, e.g., Occupational Safety and Health Administration (OSHA), Environmental Protection Agency (EPA); natural occurrences, e.g., storms, floods, and, of course, competition.

Figure 33 pictures manufacturing as defined above. This is a very broad view based on definitions used by economists, and the Federal Government. The manufacturing plant characterized by Figure 33 could be a gear factory or equally well be a steel mill, a machine shop, an oil refinery, an automotive plant, or a textile mill. For those removed from manufacturing the above definition is accepted. Those closer to the real world rarely have this broad perspective.

An extended view of manufacturing is illustrated in Figure 34 and is for an operation where the principal processes are metal cutting and/or forming, but where there is an integrated facility.

Preprocesses are those operations done in-house or by vendors which prepare the material for the primary process. The intent is not to consider all processes back to the mines, but rather to consider those preprocesses which are specifically related to the products being made, e.g., forging, casting, powder metals, and cleaning.

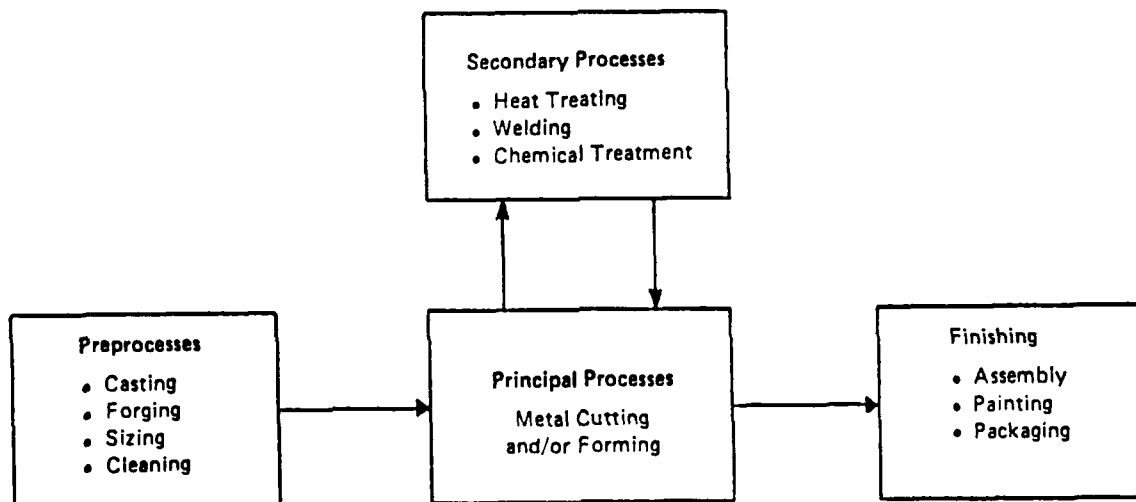


Figure 34. Extended view of manufacturing.

Secondary processes are those done on the products during the principal processes. Examples would be heat treating, plating or surface treatment. This may be done at remote sites by vendors or alternatively at a remote site within the plant. Whether done externally to or within the plant, secondary processes are accounting for an ever increasing portion of processing and production cycle time.

Finishing refers to those operations that must be completed after the machining is done. This can include painting or plating, final inspection, assembly and packaging. All of the subsequent operations that are or could be done at the same site as the machining would be included under finishing.

Principal processes represent the machining operations themselves. Numerical control machining centers and cells, automated tool changers, and so on are all aimed at improving these principal processes. Similar developments on tool material, high speed machining, water jet and laser machining, machinery and tool sensors and improved structures for machine tools are all directed at improving the primary processes.

Within each of the above processes and interconnecting them are material handling devices, e.g., ,automatic guided vehicles (AGV) and robots, as well as data control systems, e.g., manufacturing resource planning (MRP). Improvements are occurring within these supporting systems and continual improvement is anticipated. Nevertheless the optimum approach would be to minimize the need for material handling and control. One way to do this is to integrate preprocesses, secondary processes and finishing operations with the principal process.

Figure 34 and the above discussions consider the machining operation as the primary process. For the purpose of this report this obviously is and should be the emphasis. It should be obvious, however, that one plant's preliminary process can be the next plant's primary process. For example, in an operation where gear box assembly is the primary process, machining could be a preprocess. Similarly in a gear shop, heat treatment is likely to be a secondary process. Finally for a forging operation, machining could be a finishing operation. Independent of which process is primary, there are distinct advantages in integrating as many of the operations as possible.



### 3.1.3 Integrating Operation

There has been considerable integration of operations within the overall machine tool operation. Individual machines are being equipped with numerical control, automatic tool changers, automated material loading, built-in inspection and self-diagnostics. Machine tools are being interconnected with cells and centers providing for integrated production of parts with a variety of operations being conducted at one time. Ideally the raw material is picked up and not released until the part is totally machined. In the limit a flexible machining system (FMS) is capable of making one or 100 parts with equal ease with setup, tool change, and material transfer occurring automatically. With few exceptions FMS, although referred to as flexible manufacturing systems, almost without exception, really refers to flexible machining systems. In the evolving world of manufacturing, flexible machining systems will not be adequate and in the broadest sense we must strive for flexible MANUFACTURING systems. The technology future of the gear industry may well depend on this extended view of manufacturing--by accepting this broader view the gear industry may find opportunities for "leap-frog" technology.

The possibilities here are relatively unlimited. Figure 35\* shows a concept suggested by Fred Seaman of IIT Research Institute (IITRI). The figure is a conceptual design of the proposed flexible manufacturing system. It integrates lasers with robots, machine-tool modules, and machine vision under hierarchical computer controls, making it possible to go from raw stock to a formed, machined, surface-treated, subassembled product in a single manufacturing system.

There are almost unlimited possibilities available by taking an extended view of manufacturing. A few of these options are considered. These should be accepted as potentials rather than commercially viable.

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\*"Laser-Integrated Manufacturing: A Proposal to Rejuvenate the Machine Tool Industry" by F. D. Seaman and S. Rajagopal, Laser Focus/ElectroOptics, November 1983, p. 84.

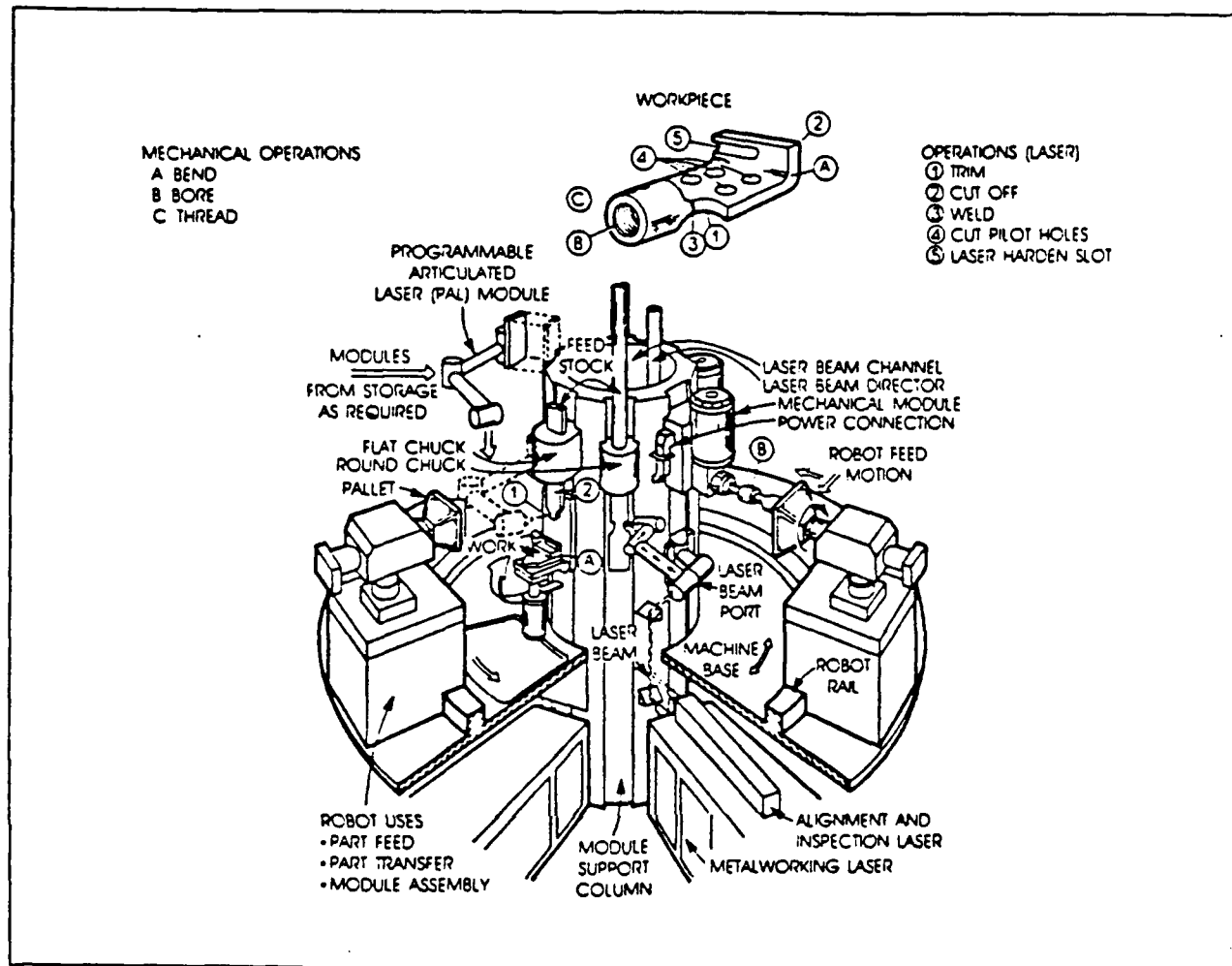


Figure 35. Conceptual design of proposed flexible manufacturing system.

Secondary Processes. The integration of secondary processes with machining offers many possibilities and is clearly the first area to consider. Heat treating can be done in the same time as gear machining using laser beam or induction heating. Since on-site heat treating could be done locally on parts as needed, it could offer other significant advantages.

Some negative factors in this approach include the fact that to change from a carburizing and hardening process to a direct hardening process involves changing the steel composition and using a process that may produce a different residual stress pattern. Testing would have to be done to ensure designers and customers that the new processing produced equivalent or better

results. The advantages are significant and include on-line instead of batch processing, shorter and less costly processing, avoidance of plating, reduction of WIP, and possibility for on-line, closed-loop inspection and process control. There appears to be many opportunities for expanding the traditional concept of machining.

Preprocessing includes producing net or near-net shape parts for subsequent machining. The question to be asked is "to what extent could these processes be integrated with machining?" Research work is under way for forging where the hammer strokes are numerically controlled so that a near-net shape part results without the need for any hard tooling. The machine tool industry could make this NC forge and integrate it with the machine tools. For forging, casting, and powder metal parts it may be possible to use NC processing to produce dies so that near-net shape parts can be produced on demand and parts made. Such "designed and built as needed" tooling could allow net shape preforms to be made on demand for modest quantities. Alternatively, a family of dies could be available allowing preforms to be made on demand in a range of sizes and shapes. Inventories, manufacturing cycle time and costs could all be significantly reduced by making near-net shape parts in real time at the site where machining is to be done. Providing the capability to produce these net shape parts and integrating this capability with traditional gear manufacturing technology could offer significant advantages in gear manufacture.

Finishing is a broad area covering a wide variety of activities. Painting, plating, and chemical treating could be done at the machining site assuming that similar processes are used frequently. One difficulty to be considered is that time-dependent processes such as plating can rarely be made into on-line processes and must be turned into batch operations. This implies holding work to make a batch but possibly the process could be under complete CNC control depending on the circumstances.

### **3.2 ORGANIZATION OF INFAC**

INFAC should be designed to achieve the purpose of an FMS but be flexible enough to allow alternative manufacturing concepts to be explored. It should also be a base for manufacturing research and educational activities related

to gears. Finally, it should be a center of information regarding gear manufacturing technology.

### **3.2.1 Design of INFAC**

INFAC should be designed by the contractor to be a flexible cell layout with movements between cells and machines to be as automated as possible. One of the purposes of INFAC should be to examine the level of CIM that is practicable. It may be that a "lights out" factory is not attainable without several iterations. The implication of the management and costing systems also requires consideration and will impact the manufacturing methods.

### **3.2.2 INFAC Research**

Where possible, all results of manufacturing research at INFAC should be finally tried on manufacture of test gears on the production line. The actual nature of the research will influence the way it is applied to the production machines. The manufacturing sequence may be made flexible enough to be included or omitted depending on the tests being made. Different management systems can be tried in parallel at the same time to develop business concepts of organizing an FMS.

However, the research agenda should focus on those aspects of gear manufacturing that are unique to gears with particular emphasis on precision gears of the type used by DOD. It is recommended that research that is generic, i.e., having wide interest to industries other than gears, not be conducted under INFAC. There are many other activities focusing on these manufacturing technologies. INFAC's goal should be to monitor these developments and introduce them into INFAC and to the gear industry when they have developed sufficiently.

As a further restriction, it is suggested that INFAC does not conduct work on gear design or on power transmission, since these activities are ongoing elsewhere and, if pursued, would detract from the major purpose of developing manufacturing technology. Again, when operational INFAC would monitor such developments and should be prepared to manufacture the products that may be required.

To be useful, gears must be assembled into a gear box. Gear box cases themselves are normally cast and subsequently finished on machining centers.

This can be done externally to the gear plant or may be done on site. In either case, there is nothing unique about the manufacture of the gear box. The requirements are essentially the same as those for a wide variety of other components used in other industries. The box is typical of the type of product that can be made very efficiently on presently available machining centers. Since this is generic, research on making gear boxes should not be conducted under INFAC.

Simple drive shafts represent essentially the same situation. There is a variety of diameters with various flats, notches, rings and slots. Again, this is a general manufacturing requirement so that research on it should not be conducted under INFAC.

Normally purchased components such as seals, bearings and fittings are also used by many other industries so are not appropriate for INFAC research support.

Left then for INFAC research is the full range of manufacturing operations required to make the gears (however complex). Traditionally, manufacture of gears starts with bar stock or forgings. There are a variety of alternative starting points that could be considered and these are viable areas for research. Using bar stock represents the extreme starting point where one begins with a piece of metal and, via various machining operations, removes all of what is not wanted. Normally this is expensive and more "near net shape" (NNS) starting materials provide advantages. Forging is an old, well established NNS procedure. It provides good properties but normally is far from the final shape desired. A wide variety of other processes including liquid forging, powder metals, hot isostatic pressing (HIP) and squeeze casting are available and should be considered viable candidates for research under INFAC. One or more of these NNS processes could significantly impact the gear industry. The INFAC manufacturing facilities would provide the site for controlled manufacturing and documentation of manufacturing technologies involved.

Material developments are expected to impact the gear industry within the next few years. For critical applications such as helicopter gears, substitution of aluminum with appropriate fiber reinforcing may replace steel as the material of choice since this can provide the same strength and wear properties at substantially less weight. Development of gears using such

alternative materials and the material developments are beyond the scope of INFAC, but INFAC must be prepared to manufacture such gears. Research into the special problems that such material changes would impose on gear manufacturing should be considered as viable areas for INFAC research. INFAC would serve as the test bed for developing and demonstrating the manufacturing technologies required for these new materials.

The "soft machining", i.e., machine blanking and forming teeth, are viable areas for INFAC research. To the extent that conventional machining centers are used to do the rough machining, this is generic and research would not be appropriate under INFAC. The actual machining of the teeth by shaping, milling, hobbing and broaching are suitable areas for research. Research relating to alternative tool materials and/or coatings are appropriate. Research into alternative techniques for producing these same shapes and tolerances are also candidate research areas. Research into achieving these goals for metal matrix composites (MMC) would also be appropriate. The instrumented equipment planned for INFAC would allow these developments to be scientifically evaluated to expedite acceptance into commercial practice.

Plating of gears is introduced primarily to protect some areas of the gear from heat treatment that is required for the teeth themselves. Other techniques for providing this protection or to reduce the need for it are suitable areas for research. Induction heat treating is one candidate as are various focused approaches for locally applying heat.

With few exceptions, hard finishing is presently accomplished by grinding. Improved grinding procedures and/or alternative processes for this hard finishing are suitable subjects for research. Evaluation of such improved grinding and other alternative techniques for hard finishing experiments need an INFAC at which they can be conducted.

The gear-making processes as presently structured depend on careful and detailed inspection at various stages of the process. Each time the part has to be inspected off the machines, there are delays. Ideally, all inspection should be done on the part while it is being made with these results used to modify the process so that all parts that are made are acceptable. Considerable opportunities exist for research to develop and demonstrate techniques for automated inspection and control to replace inspection in the gear-making

process. Development and installation of automated inspection and control on the INFAC machines would allow for development and demonstration under controlled conditions and would serve to demonstrate the commercial potential to equipment makers and users.

Although limited, the gear-related machine tool industry sector is potentially an important contributor to gear manufacturing. It is possible that some research programs with machine tool builders would be beneficial to the objectives of the program.

One of the major potentials for improving the gear-making process is to restructure the operations within the plant. This integration could be in the form of a cell, i.e., by appropriately positioning equipment so that there is minimum movement and part handling required between operations, or by providing automated material handling and moving. Either of these approaches requires "real time" interaction between all of the equipment involved and systems for controlling them. Also required are systems monitoring material flow, inspections, etc. This is a suitable area for INFAC research. These technologies are reasonably well established, but have not been extensively applied to gear making. Introducing such networking at INFAC would serve to demonstrate its potential for the gear manufacturers.

Research on the appropriate level of CIM applicable to INFAC at different stages in its development should be an ongoing activity since requirements will change as INFAC develops. Machine scheduling requirements will also increase in sophistication as development proceeds. This is an appropriate area of study for INFAC.

Some of the research can be initiated external to INFAC, but essentially all of it requires access to the type of facilities that are planned for INFAC. The challenge in laying out the INFAC research program will be to structure it so that maximum use is made of existing knowledge and facilities external to INFAC and to structure research efforts so that INFAC is used only when and where it is most appropriate. INFAC research should be initiated with the organization and researchers having the best credentials for each research area with the research moved from their location to INFAC as the research evolved.

### 3.2.3 Educational Activities

INFAC should provide the basis for an extensive training and educational program. While it will not replace the European Apprenticeship programs, it will fill a void in education and give the possibility of "hands on" experience. INFAC has to be established as part of an education center preferably one that issues degrees.

Education should proceed at several levels simultaneously. First, the INFAC can be used for shop floor operator training in all aspects of automated gear production. This could familiarize operators with CNC machines operating in cell structures. Other phases of operation could be programming and maintenance activities. Second, INFAC can be used to train manufacturing engineers at the undergraduate and graduate levels in the aspects of automated production techniques. Research can be ongoing in many aspects of manufacturing at the same time.



#### **4. ENABLING TECHNOLOGIES**

There is often a delay between the discovery of new technology and its application on the shop floor. Six technologies are listed that could be considered as part of an IMIP or Tech Mod program. Strong consideration would be made to applying them to INFAC. The Tech Mod process has been described in Section 2.2.9.1. It is anticipated that the INFAC contractor will participate with the gear makers to initiate Tech Mod programs to implement CIM-based technology.

##### **4.1 INCREASED USE OF NEAR NET SHAPE PROCESSING**

The concept of using net shapes to reduce machining time is not new and, in fact, forgings are often used as the starting point for aerospace gears. However, the use of such shapes may be capable of considerable extension with (1) shapes finished to closer tolerances, and (2) shapes made to replace cut bars.

This may reduce the machining time and also result in improved properties in the finished gears.

A variety of net shape processes can be considered including precision forging, casting and powder metallurgy.

##### **4.2 SENSING AND INSPECTION**

Machine tools are rarely built that contain inspection sensors to make dimensional checks on parts being machined. Even when CNC testers are used subsequent to machining, the test results are rarely used to interact with the tool that machined the part.

An important research activity would be to develop on-machine sensing operating in a closed loop mode that would control the dimensions of the parts being produced. Methods might include eddy current, machine vision, or laser inspection. With such sensing it should also be possible to detect tool wear and thus adjust for dimensional changes and change tools where appropriate.

### **4.3 DIRECT HARDENING**

The use of on-line, direct hardening methods to replace carburized and hardened gears should be investigated. This would eliminate a batch type process occurring in a flow production line thus preventing a bottleneck and also causes a reduction in WIP. It is suggested that nonpower transmitting auxiliary gears are considered first before drive gears are attempted. Both induction hardening and laser hardening are candidates for this methodology. The steel substituted for the low-carbon carburizing steel would be of particular importance for optimum results. The finished gear should have a highly favorable surface compressive stress system.

### **4.4 IMPROVED TOOLING CONCEPTS**

There have been many advances made on high-speed steel and vitreous wheels for grinding. An ongoing project at INFAC should be development of coatings for high-speed steel (such as TiN), ceramic inserts, cubic boron nitride (CBN) or other tool systems.

### **4.5 COMPUTERIZED SCHEDULING SYSTEMS**

It should be possible to plan complete production schedules through the factory in order to complete ship sets of gears in the same time frame. This operation has only been attempted at a few gear makers and is largely hampered by lack of manufacturing information. In INFAC, the relatively limited range of components being manufactured may prevent a full study of this factor as might be attempted at an actual gear factory for a Tech Mod program.

### **4.6 EFFICIENT FACTORY LAYOUTS**

Most layouts of plants are not optimum and have developed over the years. This often leads to unnecessary parts movement during processing. At one plant, a gear moved over three miles during processing. A revised layout reduced this distance to 200 yards. This concept would be of great importance in a Tech Mod program to be applied at a contractor's plant. It may not be optimized in INFAC where the need for layout flexibility may conflict with optimum efficiency.

## 5. CONCLUSIONS

1. The current manufacturing processes for precision gears have been assessed, and it is believed that the methodology shows little change from that used 20 or more years ago. There is evidence that CNC machines are being introduced onto the shop floor first in machining centers for blank preparation and rough turning and more recently in machines for tooth grinding.

2. There is very little evidence that any level of CIM is in use. Rarely is CAD data downloaded to a CNC system. The industry considers that the quantities of parts are too small to warrant cell operation.

3. The remaining U.S. machine tool industry has been slow in introducing CNC machines because it was thought that the sales were not there. The majority of CNC gear machine tools are of overseas origin.

4. Although some reinvestment is taking place in the gear industry, it is not at the level that will make major changes in manufacturing technology. A way of reducing the risk of investment for the gear industry is necessary.

5. There is not a strong industry/educational relationship in America as exists in Germany, and this co-venture system for conducting research could be used to advantage in the United States.

6. A two-part program supported by the U.S. Government is suggested to establish a demonstration gear factory and at the same time help gear makers reduce the risk of modernizing their own factories using a Tech Mod type or IMIP program approach.

7. The demonstration gear factory would be an instrumented factory (INFAC) which would include a flexible manufacturing system arranged in cells with an appropriate level of CIM.

8. Associated with INFAC would be a gear manufacturing related research program covering areas such as near net shape technology, metal cutting, sensing, and inspection and processing.

9. INFAC would be used as the basis for a series of educational programs at levels ranging from courses for gear operators to post graduate studies.

10. One activity with INFAC would be a technology transfer activity to keep the gear industry abreast of all manufacturing developments.

11. In conjunction with INFAC, a series of Tech Mod programs would be let to encourage gear producers to modernize their own factories. Information from the design of INFAC would be available and Tech Mod developed data could in turn be fed back to INFAC to form part of the data base.

12. Considerable effort and energy are needed to make changes in the gear industry, but this must be undertaken if the United States is to remain self-sufficient in the supply of aerospace gears.

APPENDIX A

THE TECHNICAL UNIVERSITY OF MUNICH

## THE TECHNICAL UNIVERSITY OF MUNICH (TUM)

The TUM was founded as a polytechnical college in the last century. Later, at the beginning of this century, it received the name Technische Hochschule having the status and rights of a university (e.g., to bestow the title of a Doctor-Engineer: Dr.-Ing.). In the course of the years besides the technical departments and the basic sciences (mathematics, physics, chemistry), other departments like medicine, economics, sociology and pedagogics were established. Therefore, it was decided in the 1960s to change the name to Technische Universität. Figure 36 summarizes the faculties constituting the University and its staff at the present. Figure 37 shows the considerable increase in number of students in recent years.

The historical development has been similar to that in other classical technische hochschulen in Germany (like Berlin, Braunschweig, Hannover, Aachen, Darmstadt, Karlsruhe, Stuttgart). Some of them kept the original name technische hochschule which had a good reputation in the academic field and in industry. They all have a comparable level in education and research. In the 1960s and simultaneously to the increasing number of students, a number of new institutions having different names were founded (University with technical departments, Technical University and Gesamthochschule).

**The Faculty of Mechanical Engineering.** Figure 38 shows the structure of the faculty of Mechanical Engineering at the Technical University of Munich. The Board of Faculty (including the dean) who is responsible for the general development of the faculty, the organization of education and examinations is elected every two years. The 29 chairs/laboratories are the core structure for education and research. The main part of the faculty budget is directly administered by the chairs.

The additional organization, unit of "Institute", was introduced by recent university laws to ensure better cooperation between related fields of research and to provide them with common support services such as libraries and workshops.

# 11 FACULTIES

MATHEMATICS, COMPUTER SCIENCE
PHYSICS
CHEMISTRY, BIOLOGY AND GEOLOGY
INDUSTRIAL MANAGEMENT AND SOCIAL SCIENCES
CIVIL-ENGINEERING AND SURVEYING
ARCHITECTURE
MECHANICAL ENGINEERING
ELECTRICAL ENGINEERING
AGRICULTURE AND HORTICULTURE
BREWING INDUSTRY, TECHNOLOGY OF FOOD
MEDICINE

STUDENTS: 21.822

PROFESSORS (TOTAL): 396

SCIENTIFIC ASSISTANTS: 2.538

UNIVERSITY PERSONNEL (TOTAL): 7.579

EXTERNAL LECTURERS: 209



TU München  
H. Winter

FACULTIES OF THE TECHNICAL UNIVERSITY MUNICH  
1985/86

1/105.05.17

Figure 36. Facilities of TUM 1985/86.

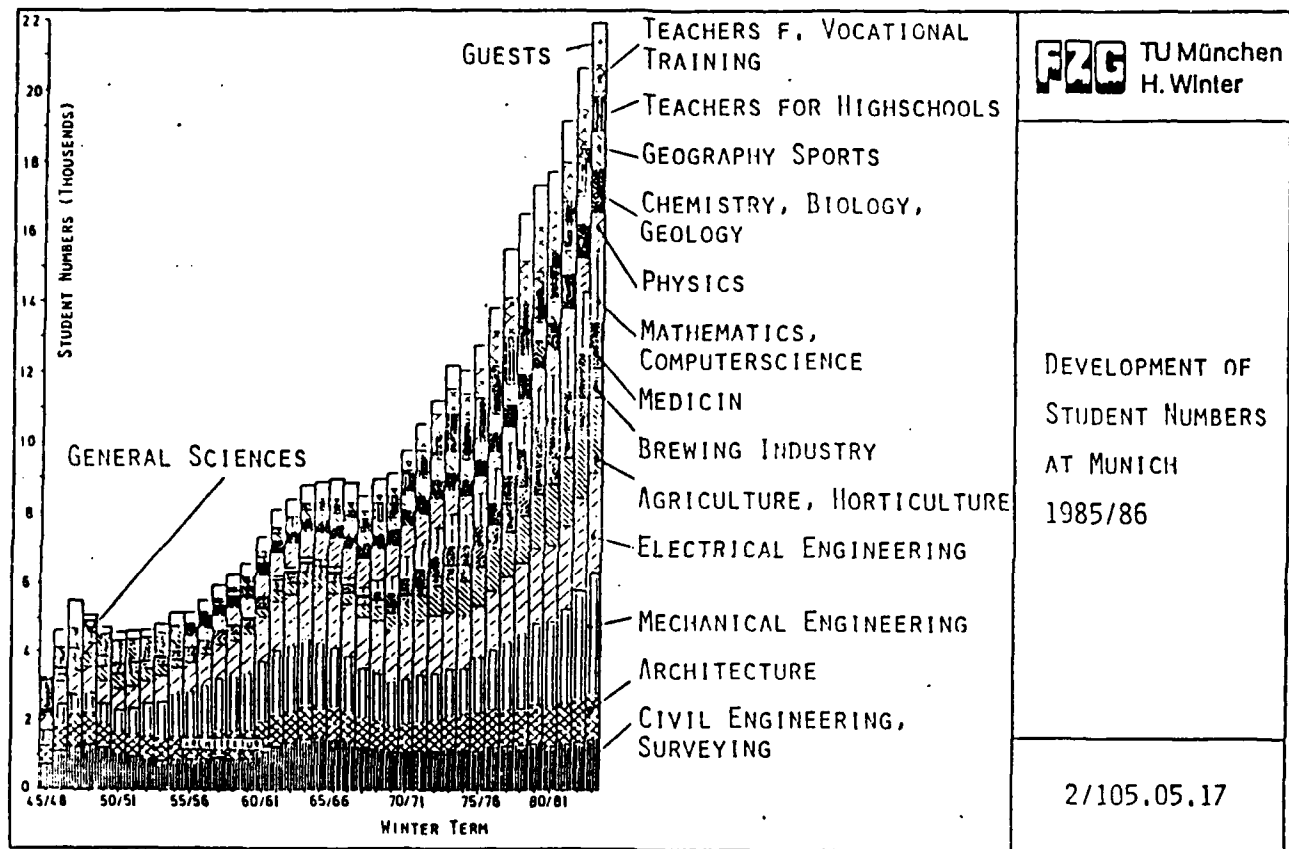


Figure 37. Student numbers.




BOARD		8 INSTITUTES		29 CHAIRS/LABORATORIES	
DEAN  PROFESSORS: 10 ORDINARIEN 4 EXTRAORDINARIEN  4 SCIENTIFIC STAFF  4 STUDENTS  2 GENERAL PERSONNEL		AVIATION/AERONAUTICS		⋮	
		CHEMICAL ENGINEERING			
		MATERIAL AND MANUFACTURING		DESIGN	
		TRANSPORTATION, TECHNOLOGY OF AUTOMOBILISM		MACHINE-ELEMENTS	
		WORKPHYSIOLOGY		CENTRE OF GEAR RESEARCH	
		MECHANICS		MACHINE TOOLS AND INDUSTRIAL MANAGEMENT	
		DESIGN			
		THERMODYNAMICS HYDRAULICS, ENERGY		PRECISION-ENGINEERING AND MECHANISMS	
 TUMünchen H. Winter		THE FACULTY OF MECHANICAL ENGINEERING TU-MUNICH 1986		3/105.05.17	

Figure 38. Faculty of Mechanical Engineering.

The head of a chair or laboratory is usually a professor (Ordinarius) who has worked in industry for a number of years. (In theoretical fields like mechanics and thermodynamics, it sometimes happens that a professor is named head of a chair/laboratory after an academic career.)

A number of chief engineers (research group managers) and all assistant engineers are responsible (under the guidance of the professor) for educating the students (lectures, tutorials, projects, examinations) and running the research work. The assistant engineers usually enter the laboratory after having finished their studies as Diplom-Ingenieur (Dipl.-Ing.) or are appointed from a position in industry. They normally work at a chair or laboratory for about six years, earning about 45.000-50.000 DM/year (in industry, salaries for young diploma-engineers vary between 50.000 and 65.000 DM/year). The duties of research and lecturing show an estimated 50-50 split. In most cases they get their doctoral degree (Dr.-Ing.) based on the research work they have carried out in these years. Afterwards they leave the university to work in industry.

Furthermore, the educational and research work of the chair/laboratory is supported by technical and administrative staff. As an example, the staffing of the laboratory for machine elements in Munich is described in Figure 39.

**Courses in Mechanical Engineering.** Under normal conditions, a student needs about five years (each of two terms or semesters) to study mechanical engineering and to receive the degree of a Diplom-Ingenieur (Dipl.-Ing.) at the average age of 25. This includes four to five semesters before and four to five semesters after the intermediate examination and about half a year for the graduation thesis. To matriculate the student must have his Abitur. At this time students show an average age of 20 after attending school for 13 and serving their national military requirements of 1-1/2 years. Compared to A-level,\* the "Abitur" is a more general examination. He must have carried out at least 12 weeks of practical work in various workshops. Another 14

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\*A-level or advanced-level is a British examination set by a group of British universities that is taken, usually prior to university entrance.

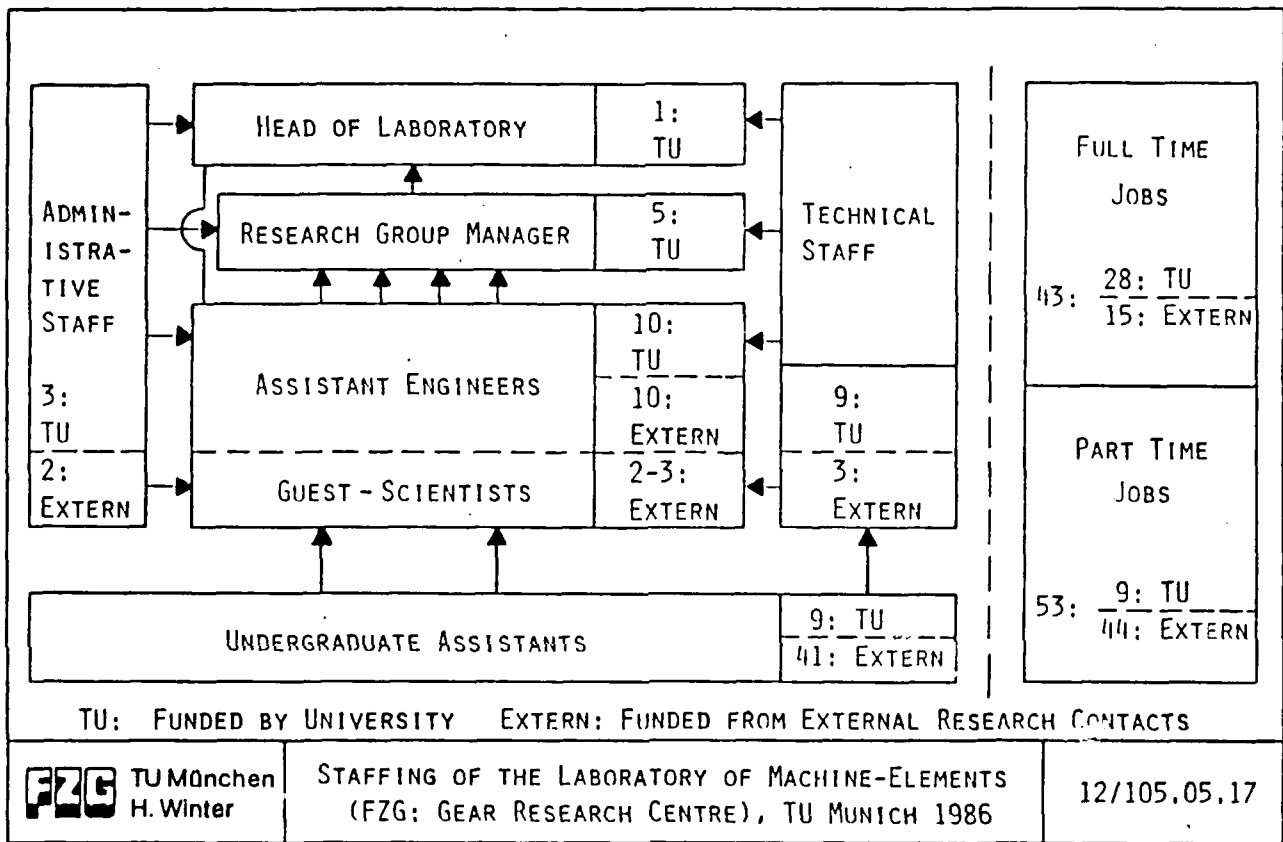


Figure 39. Staffing of laboratory for machine elements.

weeks have to be undertaken in the course of his studies before the final (Diplom) examinations.

**The Structure and Funding of Engineering Research at the Gear Research Center (FZG).** The structure and activities of this laboratory may be considered as typical. Other laboratories for machine elements or design methods in West Germany are organized and operate in a similar way but, of course, with different research interests.

As indicated by the title FZG, the research projects carried out by this laboratory are mainly related to gears, clutches and tribology (basic elements of friction, wear, lubrication and elastohydrodynamics).

Figure 39 gives a survey of the staff of the laboratory. The suffix "TU" means that the personnel are financed by the Bavarian state, "Extern" means that the personnel are financed by external sources (research associations and companies).

The function and requirements of the head of laboratory and the assistant engineers are described above.

The technical staff comprises drawing office, metallurgy, measurement laboratory and workshop staff.

The group of student assistants consists of students having passed the intermediate examinations. They help with the research and consultancy work by carrying out primarily routine investigations and standard tests.

Figure 40 shows a list of the test equipment and Figure 41 a list of the instrument equipment. Offices, labs, and workshops cover an area of about 18,000 sq ft. Apart from large components, complete parts of test rigs and devices can be manufactured in the laboratory workshop. For small-scale theoretical investigations and direct evaluation of test results, a number of medium-size computers and plotters are installed. For large-scale computer work, 10 terminals allow to communicate with the central computer system of the university (see Figure 42).

The research activities are financed by the university (i.e., the Bavarian state) and by sources outside the university. Figure 43 shows an average income of recent years. The true value of the universities' contribution in providing with rooms, equipment, heating, electric energy, water,

29 BACK-TO-BACK GEAR TEST RIGS (FZG REST RIG) FOR CENTER DISTANCE A = 91,5 MM, A = 112,5 MM, A = 140 MM UND A = 200 MM	<b>FZG</b> TU München H. Winter
3 BEVEL GEAR AND HYPOID GEAR TEST RIGS 3 WORM GEAR TEST RIGS (ELECTRICAL POWER CIRCUIT) 1 HYPOID GEAR TEST RIG FOR MEASURING EFFICIENCY 1 STATIC BEVEL GEAR TEST RIG 2 TEST RIGS FOR STUDIES ON VEHICLE - SYNCHRONISATION 1 TEST RIG FOR STUDIES ON SAFETY - COUPLINGS 3 TWIN - DISK - MACHINES 1 ANECHOIC CHAMBER 1 TEST RIG FOR STUDIES ON HEAT TRANSFER 2 RESONANCE PULSATORS (200 kN) 3 HYDROPULSATORS (60 kN, 80 kN, 100 kN)	TEST EQUIPMENT  OF THE  GEAR RESEARCH  CENTER (FZG)  TU MUNICH
FOR MEASURING FORCE, LENGTHENING, VIBRATION, NOISE, TEMPERA- TURE ETC. THERE ARE ELECTRONIC MEASURING INSTRUMENTS, TESTING INSTRUMENTS AND REGULATING INSTRUMENTS INCLUDING APPROPRIATE TRANSDUCER EQUIPMENT WITH TAPE STORES, RECORDING DEVICES, FIL- TERS ANALYZERS FOR MEASURING FORCE STRAIN, VIBRATION, NOISE, TEMPERATURE ETC.	13/105.05.17

Figure 40. Test equipment of the Gear Research Center.

<u>Air-Conditioned Measurement Chamber</u>		<u>Instruments for Oil Testing</u>	
1	Inolute Tester PFSU 1200 (Klingelnberg)	1	Infrarotspectrograph (Perkin - Elmer)
1	Universal Gear Tester UP 400 (Höfler)	1	Atomic Absorption Spectroscope (Perkin - Elmer)
1	Single Flank Gear Tester (Goulter - Micron)	1	Falling Sphere Viscosimeter (Haake)
1	Double Flank Gear Tester (Schoppe und Faeser)	1	Rotary Viscosimeter Rotovisko (Haake)
3	Instuments for Measurement Surface Roughness (Mahr - Perthen und Taylor - Hobson)	1	Titroprocessor (Metron)
1	Measuring Microscope (Leitz)		
3	High - Precision Balance (2 Mettler, Sartorius)		
<u>Metallographic Laboratory</u>			
1	Scanning Electron Microscope PSEM 501 (Phillips) with Energy Dispersive X - Ray Analysis EEDS II (Ortec)		
1	Metal - Microscope Metalloplan (Leitz)		
1	Tension Tester ( $F_{max} = 10^5 \text{ N}$ ) (Wolpert)		
	Instruments for Standardized Hardness Testing Methods (Brinell, Vickers und Rockwell), Equipment for Structural Studies		
<b>FZG</b> TU München H. Winter		INSTRUMENT EQUIPMENT OF THE GEAR RESEARCH CENTER (FZG) TU MUNICH	
		14/105.05.17	

Figure 41. Instruments of the Gear Research Center.

<p>10 Data – Terminals including Printer, Plotter Connected to Host Computer CDC Cyber 180 – 990 of Leibniz – Rechenzentrum of Bavarian Academy of Sciences Munich</p> <p>13 Personal Computers Including Periphery (6 Hewlett Packard, 7 Olivetti M24)</p> <p>1 Analog Computer 2 RAT 700 (Telefunken)</p> <p>2 Computers for Process Control, Data Aquisition and Analysis (DEC, HP)</p> <p>1 Micro VAX II</p>	<b>FZG</b> TU München H. Winter
	<p>COMPUTER FACILITIES OF THE GEAR RESEARCH CENTER (FZG) TU MUNICH</p>
	<p>15/105.05.17</p>

Figure 42. Computer facilities.

FINANCIAL RESOURCES FROM THE UNIVERSITY

PERSONNEL	1.800.000	DM
MATERIAL	90.000	DM

EQUIPMENT, ROOMS, HEATING, ELECTRIC,  
ENERGY, WATER, GENERAL ADMINISTRATION  
IS PROVIDED BY UNIVERSITY

FINANCIAL SOURCES OUTSIDE THE UNIVERSITY (EXTERNAL)  
(PERSONNEL, EQUIPMENT, MATERIAL)

RESEARCH ASSOCIATIONS (FVA, BMFT, ...)	860.000	DM
DFG	150.000	DM
FZG-ACTIVITIES, E.G. TESTS	100.000	DM

• FVA: GEAR RESEARCH ASSOCIATION OF THE GERMAN INDUSTRY  
BMFT: FEDERAL MINISTRY FOR RESEARCH AND TECHNOLOGY  
DFG: GERMAN RESEARCH ASSOCIATION

**FZG** TU München  
H. Winter

FINANCING OF THE CHAIR FOR MACHINE-ELEMENTS  
(GEAR RESEARCH CENTER, FZG) IN 1986

16/105.05.17

Figure 43. Financing.



general services, and general administration is difficult to estimate. But this contribution is certainly important in keeping down the nominal, i.e., direct research cost, and in this way indirectly supports research ordered by external parties.

Figure 44 gives a summary of the research projects running at the FZG Research Center and their financial background.

There is much cooperation between research institutes and their partners in industry and with research organizations and state administrations.

**Research Financed by the FVA (Forschungsvereinigung Antriebstechnik - Research Association for Power Transmission).** The Association has about 50 company members who contribute to the research budget in proportion to their size. These are gear and bearing manufacturers, automotive companies, and other producers of various transmission elements. The Federal Government contributes to the research budget in direct proportion to the total amount obtained from the member companies. On this account, companies are obviously more interested in cooperation with the Association.

Figure 45 summarizes on the organization of the Association and its working procedure. The members forward proposals for research projects which they feel to be of common interest and not detrimental to their competitive position. A technical committee and a board of directors decide the priority of the research projects. Correspondingly, invitations to tender are sent to universities and private laboratories qualified and interested in such research work. After checking technical quality, price and deliver time, a competent committee of company members decides where the research contract shall be placed. To receive government support, a detailed research proposal including costs for personnel and materials must be submitted to and accepted by experts appointed by the government.

Twice a year the representatives of the research laboratory have to report on the progress of the work at meetings with specialists from the member companies. (There are research committees for design, computer programs, materials and lubrication.) Once a year the Association holds a conference where representatives of the laboratories report on major results and have discussions with the audience representing all member companies. The final results of each research project are compiled in a report which is

SPONSOR	SUBJECT	COSTS THOUSAND DM	DURATION (YEARS)	<b>FZG</b> TU München H. Winter
FVA	PITTING RESISTANCE	390, 280	4,3	RESEARCH PROJECTS OF THE GEAR RESEARCH CENTRE (FZG) 1984, FINANCED BY EXTERNAL SOURCES
	GREY STAINING	360	3	
	TOOTH ROOT STRENGTH (FATIGUE)	450	3	
	DYNAMIC TOOTH LOADS	320	3	
	HEAT BALANCE OF GEAR BOXES	300	4	
	WEAR AND EFFICIENCY OF WORM GEARS	350	3	
DFG, WITH CONTRIBUTION OF COMPANIES (KLINGELNBERG) (DEMAG, MALME- DIE, KRUPP) (TU)	BEVEL GEARS	450	3,5	* RESEARCH ASSOCIATION OF THE GERMAN INDUSTRY WITH CONTRIBUTION OF COMPANIES
	SAFETY COUPLINGS	350	3	
	TOOTH STIFFNESS	400	5	
	HIGH SPEED SCUFFING	490	3	
FKM*	NOTCH SENSIVITY	320	3	
BMFT, WITH CONTRIBUTION OF COMPANIES (BAYER) (DAIMLER-BENZ) (MBB)	SYNTHETIC LUBRICANTS	400	3	
	SYNCHROMESHES	630	5	17/105.05.17
	EHL-CONTACTS	540	3	
AUDI	HYPLOID GEARS	450	3	

Figure 44. Summary of research projects.

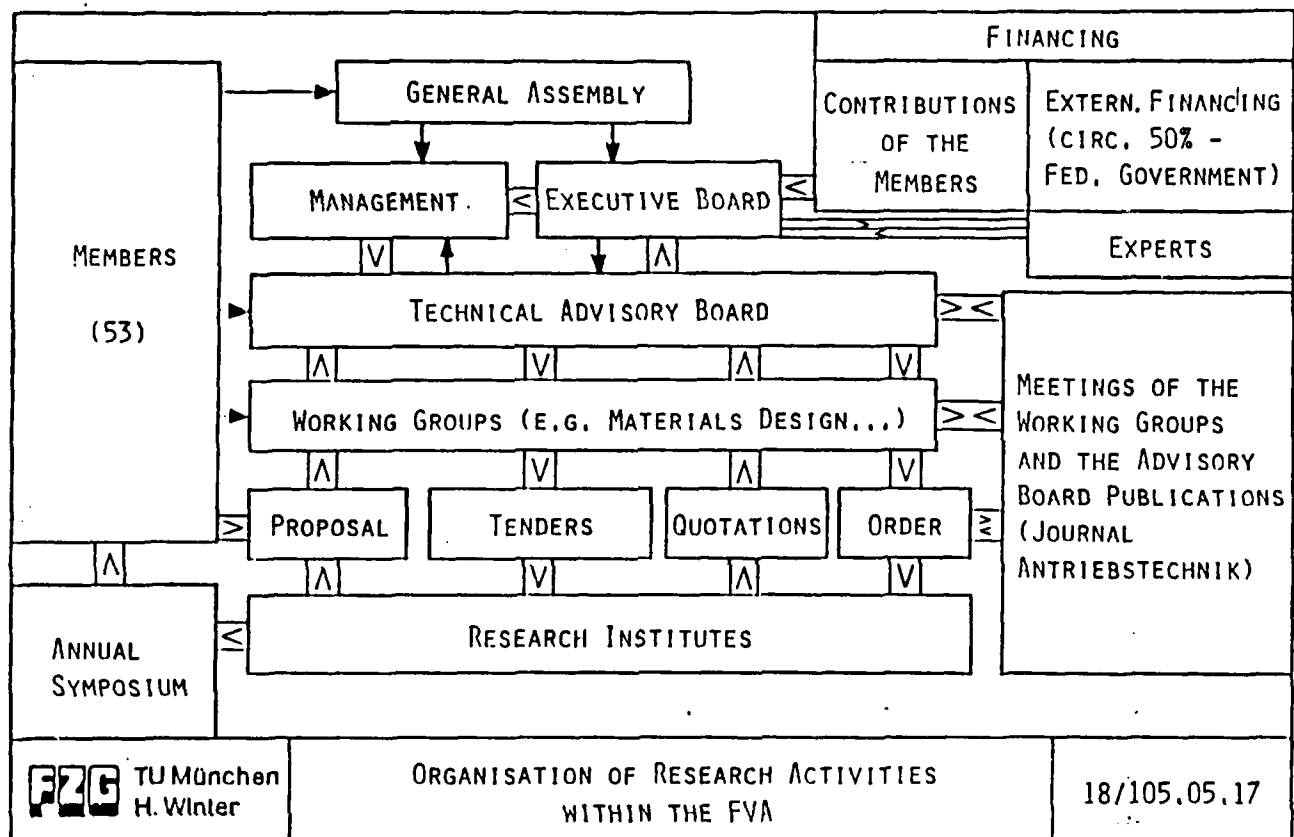


Figure 45. Organization of research activities.

printed by the Association and distributed to their members. The reports are normally published after their completion and research institutes may publish on the essential scientific results in journals in agreement with FVA representatives. To facilitate the introduction of essential knowledge to practical applications, condensed versions of the research results in the form of rules and guidelines are printed as working sheets (Arbeitsblätter) which are available only to FVA members. Figure 46 gives an impression of the field of research which has been sponsored by the Association.

Research Financed by the BMFT (Bundesministerium für Forschung und Technologie - Federal Ministry for Research and Technology). The BMFT sponsors a different form of cooperation between industry and research institutes. If a company and a university institute have mutual interest in a certain research subject, the ministry compensates the full costs for the institute and a certain percentage of the expense the company. If the company later decides that the results of the research work should only be used for the sole benefit of the company, the whole contribution of the ministry must be returned. Otherwise the results must be published. The procedures for reporting are similar to those of the FVA.

Research Financed by the DFG (Deutsche Forschungsgemeinschaft - German Research Society). The DFG is the most important organization for sponsoring independent research in all fields, especially basic research. If the university thinks that a principal technical problem in their field needs more detailed consideration and they have the basic research facilities at their disposal, they can apply for financial support to the DFG. A complete research proposal covering a description of the problem and the intended research approach as well as the research costs are submitted for critical examinations by at least two experts. Sometimes interested companies are asked to cooperate by contributing test components or test rigs. Representatives of such companies are invited to join seminars at which results and problems of the research work are presented and discussed. The budget of the DFG is completely financed from tax income by the Federal Government. The research reports must be published.

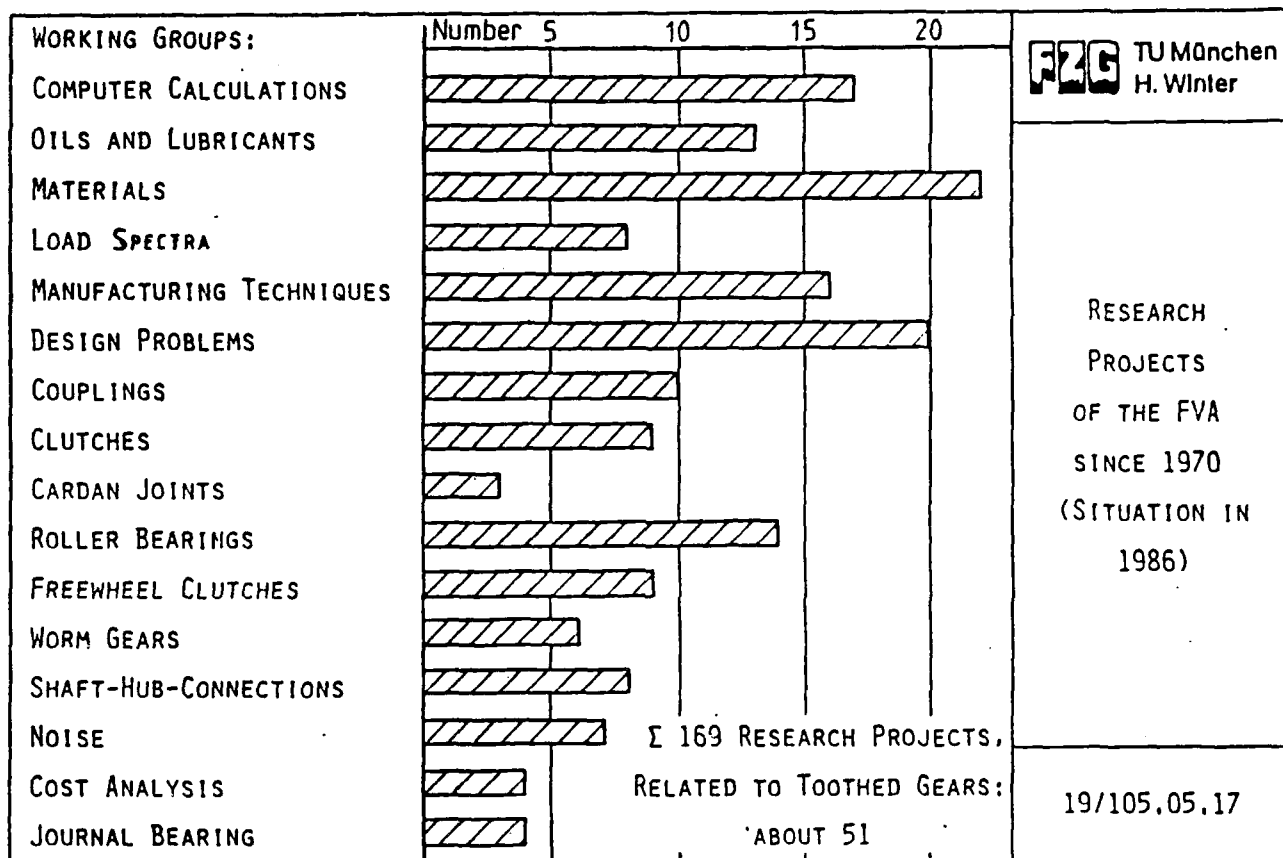


Figure 46. Research projects of the FVA.

Direct Cooperation Between a Company and the Research Institute. This is another way of cooperation. The conditions are settled by individual contracts to obtain closer partnership with industry, i.e., direct sponsorship.

Financing of Dissertation Work. Only some of the doctoral dissertations and the corresponding experimental or theoretical research work is completely financed by the University. Usually the means of the research financed by external sources described above are used as a basis for dissertations. If the association or the company is only interested in more or less practical rules, the research must be completed by thorough scientific (theoretical and/or experimental) investigations to achieve an adequate academic standard, suitable for a dissertation. An assistant engineer normally needs six years to complete this part of his education. Besides practical results of the research work which can be applied directly by our partners in industry, the research has enabled us to recognize the need and to make proposals for more fundamental basic research. Bright young engineers have gained experience in research work and in the field of gearing. Quite a number of them have now achieved positions of importance in the German gear industry.

APPENDIX B

THE UNIVERSITY OF AACHEN

## THE UNIVERSITY OF AACHEN

The Laboratory for Machine Tools and Industrial Management (WZL) of the Technical University Aachen (RWTH) has set itself the goal of producing practicable industrial solutions for the rationalization of production processes. A balanced mixture of fundamental and applied research covers a wide range of work relevant to all industrial sectors. Various areas of company operations are dealt with, including development and design, organization, planning, production, assembly and quality assurance.

In the process of achieving this goal, the WZL has developed into one of the most efficient institutes of its kind. Modern buildings house office, laboratory and workshop facilities. An extensive state of the art machine park is supplemented by high-quality computers, measuring instruments and analytical equipment. With its own design office and mechanical and electrical workshops, the institute is able to develop and fabricate prototypes up to the production stage.

The organizational structure of the WZL, with its division into departments for organization, production resources, production technology and quality assurance, is consciously designed to mirror company structures and cover all tasks arising in production processes.

A balance is maintained between fundamental research and applied development, ensuring rapid application of scientific results. Long-established contacts with noted research bodies and a host of companies at home and abroad keep the institute in the forefront of international developments and ensure that research policies remain closely wedded to industrial needs. The intimate links between this broad range of research activities and the institute's teaching work equip the young production engineer with the intellectual tools he needs for his future tasks.

By virtue of the independent responsibilities they undertake, research engineers at the WZL acquire skills and experience particularly qualifying them for positions in higher management.



Over and above its university teaching responsibilities, the WZL has always placed special emphasis on keeping the practicing engineer fully informed of the latest developments in his field. Over the years, an imposing variety of seminars, conferences and colloquia have successfully passed on the newest technologies, methods and working procedures in a form closely geared to industrial needs.

### The History of WZL

1906. In 1906, Prof. Dr.-Ing. e.h. Adolf Wallich's was appointed to the Chair of Machine Tools and Industrial Management at the Technical University in Aachen. Professor Wallich's personal achievement was to establish the new science of production engineering firmly among the classical technical disciplines, taking up Taylor's theories and disseminating them more widely.

1908. In a small experimental workshop in the cellars of the Technical University, systematic studies of the machining process were made, earning national and international acclaim.

1924. In 1924, despite the difficulties of inflation and economic crisis, the tireless zeal of Professor Wallich's and the close support of local industry succeeded in raising sufficient funds to build an independent institute.

1936-1938. Prof. Dr.-Ing. Herwart Opitz was appointed to succeed Professor Wallich's in April 1936. In 1938, the laboratory was considerably extended to accommodate facilities for research into the latest problems of machine tool construction and production engineering. Under Professor Opitz' leadership, the WZL went from strength to strength, becoming one of the most modern and renowned research bodies of its kind. Steady enlargement of the laboratory was interrupted only by the war years.

1943/1944. In 1943 parts of the institute were evacuated to Eynatten and Eupen and in 1944, after a direct hit during a bombing raid at Whitsun of that year, the institute as a whole was transferred to Eisenach.

1946/1948. In 1946, Professor Opitz, aided by a few colleagues, began the task of reconstructing the almost completely destroyed institute in Aachen. On completion of reconstruction work the first Aachen Machine Tools Colloquium was staged under unimaginably difficult conditions in 1948. The

colloquium was largely taken up with machine tool topics and aimed chiefly at providing a forum for the exchange of experience and ideas. No one viewing these modest post-war beginnings could have recognized in them the seeds of an event which was to become an international meeting point for experts from all fields of production technology, attracting more than 1700 participants from all over the world.

With the economic boom of the late 1950s, there was an intensification of research work clearly mirrored in the increase in staff numbers from 123 in 1956 to 491 in 1980. The number of scientific workers rose from 30 to 128 graduate engineers over the same period.

1968. Machining and electrodischarge machining are among the main fields of research at the WZL, and in 1968 a department specializing in these two disciplines was created.

1972. In 1972 the foundation stones of the long-planned machine hall and office building were laid. These new buildings were needed to gather research groups scattered throughout the city under one roof and to create the space for new research activities.

1973. With the growing importance of production engineering in research and teaching, the work of the Chair of Machine Tools and Industrial Management and the Department of Machining Technology was reorganized under three Chairs for:

- Production Systems
- Production Engineering Technology
- Machine Tools.

In addition, a new field of research was covered by the creation of a Department of Metrology in Automated Production.

After this reorganization, the three new departments shared responsibility for tasks in the field of metal-forming technology. A metal-forming department had been approved by the Ministry of Education in 1962, but prior to reorganization, lack of equipment had seriously restricted teaching and, especially, research activity in this field.

Before his retirement after 37 years in office, Professor Opitz passed on responsibility for the direction of the Laboratory to

- Prof. Dr. Ing. Dipl. Wirt.-Ing. W. Eversheim
- Prof. Dr. Ing. Dr. h.c. W. König
- Prof. Dr. Ing. M. Weck.

Prof. Dr. I. T. Pfeifer was appointed to head the Department of Metrology.

1982. The Society of Manufacturing Engineers (SME) of the United States granted the SME Education Award for 1982 to the WZL in recognition of its outstanding achievements in engineering education, citing the WZL's "unrivalled international reputation as a training institution for engineers which deserves to act as a model throughout the world."

1986. In January 1986 the Fraunhofer Institute for Production Technology (IPT) moved to spacious new buildings immediately adjacent to the WZL.

In June of the same year, the WZL celebrated its 80th year as a research institute. Together with numerous former colleagues and representatives from all sections of public life, the Prime Minister of North-Rhine Westphalia, Johannes Rau, took part in the jubilee celebrations.

The Association of German Machine and Plant Buildings (VDMA) awarded the WZL the first German Machine Building Prize, underlining once again the close bonds between research and industry which have so effectively encouraged the early transfer of research results to industrial practice.

Organization and Fields of Research. With the aim of uniting all areas of production engineering within a single institute, the Laboratory for Machine Tools and Industrial Management combines the Chairs of Production Systems, Production Engineering Technology and Machine Tools and Metrology in Automated Production in a common organizational structure.

This form of organization means that the various departments are not structured on classic vertical lines according to particular production processes or machine types, but divided horizontally into fields like organization, production or design. This has the advantage that problems which are of fundamentally the same nature, for example analysis of vibration phenomena on cutting or on noncutting machine tools, can be solved using the same methodology, analytical tools and equipment. The close cooperation between the various disciplines within the Laboratory also ensures optimal consideration of all influencing variables affecting a particular problem. The WZL

collaborates closely with the Fraunhofer Institute for Production Technology (IPT) in Aachen. This institute, organized along the same lines as the WZL, has a defined sphere of activities in the fields of process technology, production machines, metrology and planning and organization. Scientific and technological research is concentrated on the use of nonconventional sources of active energy, the processing of innovative materials, conventional process optimization, precision processing, quality testing and investment planning. As an institute of the Fraunhofer Society for the Promotion of Applied Research, it is primarily involved in applied research projects commissioned by industry.

Overall direction of the WZL is entrusted to a directorial board, with the managing directorship passing to the occupant of each professorial chair in turn. Research activities within the institute are assigned to various research groups according to the main aspect of the research involved. Interdisciplinary work within the research groups, aimed at complete integration of all tasks from design to operations scheduling and control or the actual production process, is particularly evident in the fields of gear making and gear train research. The corresponding research group is assigned to both the Chair of Production Engineering Technology and the Chair of Machine Tools. Courses offered by the Institute are continually updated to include the results of the latest research and are based not only on lectures organized directly by the appropriate Chair, but on a great number of special lectures dealing with particular aspects of production engineering. Students are also given the opportunity to participate in seminars, laboratory practicals and colloquia, and are offered help and supervision in the writing of graduate and post-graduate theses. The Institute's outstanding achievements in the field of teaching are underlined by the granting the the SME Education Award in recognition of the WZL's excellence as a training institution for engineers in the field of applied production technology, research and development.

The exceptional level of cooperation between the Laboratory and industry in the research and development field is documented by the presentation in 1986 of the first German Machine Building Prize ever awarded by the Association of German Machine- and Plant-Builders (VDMA) to the WZL. Both research and teaching are supported by central services, including a reference library,

documentation center, technical office and mechanical and electrical engineering workshops.

**International Cooperation.** In 1979, the responsible ministers concluded a bilateral agreement on cooperation between German and Norwegian research institutes. The agreement envisaged coordination of research and development activities in the CAD/CAM field, with the objective of increasing productivity in German and Norwegian industry. Funding for this cooperative project, which commenced in 1981 and is planned to extend until the end of 1987, is at present provided jointly by Norges Teknisk-Naturvitenskapelige Forskningsrad (NTNF) and the Kernforschungszentrum Karlsruhe GmbH (KFK) acting on behalf of the Bundesminister für Forschung und Technologie (BMFT). The working group, referred to by the acronym "APS", includes the following organizations:

- SINTEF (Production engineering Laboratory NTH-SINTEF)
- SI (Central Institute for Industrial Research)
- WZL (Laboratory for Machine Tools and Industrial Management of the RWTH Aachen)
- IPK (Fraunhofer Institute for Production Plant and Design Technology, Berlin)

and is supported by close collaboration with pilot users and software firms.

Research work within the framework of the project is aimed at developing a system for integrated generation of production documentation. All activities, from concept and design to output of production documentation, are to be aided by the system. Some of the main aspects dealt with are system architecture, concept design phase, geometry processing and operations scheduling. A wide range of applications for the eventual solutions is ensured by use of FORTRAN as a programming language and a strictly modular construction of the entire system.

In order to permit modern, effective research management, the program is broken down into two phases. The first phase was devoted to the design and realization of basic modules for a CAD/CAM system based on previous development carried out at the participating institute. Experience gained in the first phase will be used in the second phase to extend and integrate individual modules, incorporating the latest advances in hardware and software.

An important overall requirement in both project phases is that developments should be oriented to practical industry and should be made available to industrial firms as soon as possible.

#### **CIRP - An International Research Organization**

The CIRP research association (College International pour l'Etude Scientifiques des Techniques de Production Mecanique) is a scientific body, whose aim is to encourage research and publish research results in the field of production technology. This international research body counts among its members some 250 scientists from 36 countries, including the occupants of the professorial chairs at the WZL. Annual conferences encourage intensive exchange of experience at the international level and provide an opportunity for presenting research results for discussion and comparison with accomplishments in other parts of the world.

International cooperation at the WZL also includes intensive contacts with research institutes in Mexico, Columbia, Chile, China, India and Brazil, where a partnership agreement has also been concluded.

**ESPRIT - European Strategic Program for Research into Information Technology.** Under the European Strategic Program for Research into Information Technology, the WZL is participating in three projects.

Project 688, SIM-OSA, is aimed at developing a European CIM architecture and setting up guidelines.

Computer integrated manufacturing is based on the concept of a continuous information and data flow. The computerization of design, planning and production has, however, already created innumerable stand-alone solutions, often incapable of communicating with one another. The project aims at linking these stand-alone solutions via an OSA (Open System Architecture) model. The introduction of an open architecture of this type has implications not only for the structure of information and data, but for that of the company itself. Appropriate models are therefore being developed for the various parts of the company organization. Collaborating in this project, known as AMICE (European Computer Integrated Manufacturing Architecture), are a total of 19 European firms from Germany, Italy, France, the United Kingdom, Belgium and Denmark.

Computer manufacturers, software houses and users from various sectors of industry are represented. The WZL is the only research institute to be invited to participate.

Project 812, CIM-Centre Genoa, is charged with setting up a research center for the development and testing of technologies in the fields of electronics, mechanical engineering and software engineering relevant to computer integrated manufacturing.

The objectives of the project are research, development and testing of methods, implemented functions and resources suited for attaining integrated system solutions by means of the automation of plant and the selection of appropriate forms of organization, while incorporating functions already installed by the project participants.

The research center will be located in Genoa. Development of the center is in the hands of an international consortium composed of industrial concerns and university and research institutes from a number of European countries (Italy, France, Belgium, the Netherlands, Germany).

Project 419, the Open-CAM System, is concerned with the creation of CAM architectures which are capable of further extension. "Open" in this sense is to be understood as denoting the ability to integrate functionally separate sections of the production process with differing levels of automation under a common "factory management".

Universally-applicable systems for describing existing production specifications are to be devised and resources created for translating the resulting input data into proposed solutions.

The descriptive systems will be continuously compared with industrial practice and generalized. For this purpose, a suitable area of production has been selected in one of the eight companies participating in the project. The project methodology is used to catalog performance specifications for this area, covering both machines and software.

The catalog embraces necessary equipment, future production planning and control software and control software for the plant itself.

In the final project phase, results will be implemented in the form of a model production plant.

Innovations and Contacts. The WZL regards it as one of its normal responsibilities to place the results of state of the art research at the immediate disposal of industry and to incorporate advances in knowledge in its teaching activities.

Trade associations, companies, research bodies and sources of public funding, without whose intensive support no scientific research geared to industrial needs would be possible, are continuously informed of the current status of research projects. Apart from direct information to sponsors, for example in the form of progress or final reports, numerous publications in academic and professional journals, some 180 annually in recent years, help to satisfy information needs. The WZL itself edits a specialist journal, the "Industrieanzeiger".

Doctoral theses written at the WZL, some 15 or 20 each year, are comprehensive presentations of special areas of scientific interest, extending beyond the confines of an individual project. Lectures and contributions to scientific conferences present results to scientists and practicing engineers. Among these activities are the workshops organized by the Association of German Machine Tool Makers (VDW) and the German Engineers' Association (VDI) in collaboration with the WZL.

In this context, special mention should be made of the triennial Aachen Machine Tools Colloquium (AWK), offering a forum for contributions prepared in collaboration with practicing engineers and serving to strengthen the bonds between research and industry.

The exchange of information with engineers from a wide range of industries is greatly stimulated by participation in various committees, working groups and training seminar organized by such bodies as the VDMA, VDW, DIN, VDI, VDEh, VDG, VDS, DKG, DGM, FVA, FVV and RKW.

The WZL is frequently represented at trade fairs, both to ensure that it keeps up to date on recent developments and to present its own projects carried out in collaboration with industry.

The WZL is also engaged in a regular exchange of experience and results with other university institutes, not least the 17 members of the Universities Production Technology Group (HGF) created at the instigation of Prof. Dr. Ing.



E.h. Adolf Wallich, the founder of the Chair of Machine Tools and Industrial Management at the RWTH Aachen.

In addition, the WZL maintains close cooperation and exchange of information with institutes and scientists from other countries active in the fields of machine tool building and production technology.

Apart from the activities mentioned above, results from broader research areas are disseminated in the form of research reports and book publications, including a number of scientific series edited from the laboratory. Information on internal activities at the WZL appears at regular intervals in the WZL bulletin.

Within the institute, WZL colloquia serve to ensure the flow of information from department to department. The Productions Technology Colloquium conducted several times each term provides representatives of industry, research workers at the institute, and students with an opportunity to keep up to date with practical problems and insights.

The WZL maintains its close contacts with industry through common research projects and consultancy and advisory services on specific company problems. In many areas, this gives companies access to analysis and problem-solving services which could not be provided using internal staffing and technical resources.